Flood modelling and predicting the effects of land use change on the flood hydrology of mountainous catchments in New Zealand using TopNet

A thesis submitted in partial fulfilment of the requirements for the degree of

Master of Engineering in Civil Engineering

in the University of Canterbury

by Eugene Beran

University of Canterbury

2013

Abstract

The management of New Zealand's freshwater resources has come under increasing pressure from different industrial and environmental stakeholders. Land use change and the pressure it can put on water resources has been a significant issue regarding resource management in New Zealand. A significant mechanism driving land use change has been the growth of forestry, dairy farming, and other agricultural industries. Improvements in agricultural and forestry science and irrigation techniques have allowed new, previously less arable areas of New Zealand to be subject to land use change, such as the conversion of tussock grassland to pasture in steep, mountainous regions in the South Island. Studies regarding the effects of land use change in such catchments, especially with focus on flood hydrology, appear to be limited, despite the importance of managing catchment headwaters to minimise flood risk downstream.

The TopNet model was used in this research project to evaluate the potential effects of land use change on flood hydrology in mountain catchments. It is a semi-distributed continuous rainfall-runoff model developed by the National Institute of Water and Atmospheric Research (NIWA). It has been widely used in New Zealand, and applications have included modelling water yield and the effect of climate change in catchment networks. However, it was not developed specifically for predicting flood flows. Hence, testing the model for flood peak prediction in mountainous catchments was also performed, and may show that TopNet can be a useful tool in resource management in New Zealand.

The Ahuriri and Pelorus River catchments were used in this investigation. Both are steep catchments located in the South Island. The Ahuriri River catchment, in the Waitaki Basin on the eastern side of the Southern Alps, is a semi-arid catchment dominated by tussock grassland. The surrounding catchments are heavily influenced by infrastructure for hydroelectric power (HEP) generation and more recently irrigation for dairy farming. The Pelorus River catchment is located at the northern end of the South Island. It is primarily covered in native forest, but adjacent catchments are subject to agricultural and forestry development.

The ability of the TopNet model for each catchment to predict flood flows were tested using a selection of historical flood events. Rainfall input to the model was at a daily timestep from the virtual climate station network (VCSN), and the method of disaggregating the daily estimate into an hourly rainfall series to be used by the model was found to have a significant

influence on flood prediction. Where an accurate historical rainfall record was provided from a rainfall gauge station within the catchments, the disaggregation of the daily rainfall estimate based on the station data produced a significantly more accurate flood prediction when compared to predictions made using a stochastic disaggregation of the daily rainfall estimate.

The TopNet models were modified to reflect land use change scenarios: the conversion of tussock grassland to pasture and the afforestation of tussock in the Ahuriri River catchment, and the conversion of forested land to pasture and the harvest of plantation forestry in the Pelorus River catchment. Following a past study into modelling the effects of land use change using TopNet, three key model parameters were modified to reflect each land use scenario: saturated hydraulic conductivity K_S, canopy storage capacity, and the canopy enhancement factor. Past studies suggested a wide range of suitable values for K_S, although also acknowledged that K_S depends heavily on the specific catchment characteristics. A sensitivity analysis showed that K_S had a significant influence on flood peak prediction in TopNet. It is recommended that further investigation be conducted into suitable values for K_S.

TopNet appeared to predict the effect of land use change on flood magnitude in mountainous catchments conservatively. Past studies of land use change suggested that the effect on flood flows should be significant, whereas TopNet generally predicted small changes in flood peaks for the scenarios in each catchment. However, this may suggest that the topography, geology, and soil properties of steep catchments are more important to flood hydrology than land cover. Further investigation into the effect of such catchment characteristics is recommended. Nevertheless, TopNet was shown to have the potential to be a useful tool for evaluating and managing the effects of land use change on the flood hydrology of mountainous catchments in New Zealand.

Acknowledgements

I would like to thank Dr Brian Caruso for his support throughout this research project. His expertise, encouragement, and feedback were most appreciated. I would also like to thank Dr Christian Zammit of the National Institute of Water and Atmospheric Research for providing access to the TopNet model. His knowledge of the model and advice on modelling techniques and New Zealand hydrology proved invaluable. Thanks are also due to Dr Tonny de Vries for her constructive feedback during this research project, and to my family and friends for their continued support.

Table of Contents

Figures

Tables

Abbreviations

AEP	Annual Exceedance Probability
ARI	Annual Return Interval
DMIP	Distributed Model Intercomparison Project
ECan	Environment Canterbury
GEV	Generalised Extreme Value
GNS	New Zealand Institute of Geological and Nuclear Sciences
HEP	Hydroelectric Power
LUC	Land Use Capability
MAF	Ministry of Agriculture and Forestry
MDC	Marlborough District Council
MFE	Ministry for the Environment
MPI	Ministry for Primary Industries
NIWA	National Institute of Water and Atmospheric Research
NSE	Nash-Sutcliffe Efficiency Value
PCE	Parliamentary Commissioner for the Environment
PEPF	Per Cent Error in Peak Flow
PRR	Project River Recovery
RMA	Resource Management Act (1991)
TDC	Tasman District Council
TPE	Time to Peak Error
UWB	Upper Waitaki Basin
VCSN	Virtual Climate Station Network
WCWAB	Waitaki Catchment Water Allocation Board

1 Introduction

The United Nations ranked New Zealand highly in a global assessment of freshwater resources (UNESCO, 2009). However, the management of New Zealand's freshwater resources has come under increasing pressure from industrial and environmental stakeholders. A key issue has been changing land uses and the associated change in hydrology and freshwater demand for the affected areas (Addison, 2009; Aqualinc, 2010; Mosley & Pearson, 1997). The most significant driving mechanisms behind land use change are a high demand for dairy and other agricultural and pastoral industries, advancements in agricultural and forestry science and techniques to optimise profitability, and more recently the appeal of carbon sequestration under the Kyoto Protocol. Land use change has become an important issue in mountainous catchments in New Zealand, and research regarding the effect of land use change on the hydrology of affected catchments appears to be sparse, especially with regard to flood frequency and magnitude. Furthermore, the change in flood hydrology that can result from land use change appears to be somewhat neglected in local resource management legislation, despite the importance of flood control in the Resource Management Act 1991 (RMA) (Painter, 2004).

Hydrologic modelling, or rainfall-runoff modelling, has been a useful tool for evaluating and managing freshwater resources and predicting flood magnitudes and frequencies in New Zealand and across the globe. A number of different models have been used in New Zealand in recent years, including the TopNet model, which has been applied to a number of catchments across the country. The TopNet model is a semi-distributed continuous hydrologic model (Bandaragoda, Tarboton, & Woods, 2004). It was developed by the National Institute of Water and Atmospheric Research (NIWA) for the continuous modelling of New Zealand catchments and has been shown to be able to model catchment runoff with a high level of accuracy (Reed et al., 2004). Hence, the model may be able to be applied to steep, mountainous catchments in New Zealand. However, TopNet is a continuous model and was not specifically developed for the modelling of high flow events. Nevertheless, TopNet may be able to model flood events in steep catchments and predict the effect of land use change on the flood hydrology of such catchments. As a result, the model may be a useful tool in land use and freshwater resource management in New Zealand.

1.1 Hypothesis

The hypothesis of this research project is that land use change may have a significant effect on the flood hydrology of mountainous catchments, and that TopNet may be a useful tool to model and evaluate this effect.

1.2 Research Objectives

The following research objectives have been identified in order to test the hypothesis of this research project:

1. Analyse land use change and management practices in New Zealand and effects on floods, with a focus on mountainous catchments;
2. Evaluate the ability of existing TopNet models to estimate flood magnitudes and frequencies and provide flood predictions for current land use scenarios for two case study catchments in mountainous regions of New Zealand;
3. Modify the existing model to reflect potential land use change scenarios in each case study catchment and use the model to predict flood events under such land use conditions; and
4. Discuss and compare the model predictions for current and potential land use scenarios to evaluate the model performance, and discuss potential impact of the findings on current land and water management practices.

1.3 Thesis Structure

Following the introductory chapter of this research project, Chapter 2 contains a review of current literature pertaining to land use trends and hydrologic modelling with a focus on the New Zealand context and steep mountainous catchments. Under the umbrella of land use trends, the driving mechanisms for land use change in New Zealand are described, specifically in the areas of agriculture and forestry. The effect of these land uses on the hydrology of affected areas is also outlined. The review of hydrologic modelling covers a brief history of hydrologic modelling, different types of models, the use of a variety of models in New Zealand, and the TopNet rainfall-runoff model.

Chapter 3 outlines the methodology for this research project. This includes the method by which two suitable catchments were selected for use in the project, and a detailed description of the land use and hydrological characteristics of each catchment. The development, governing equations, and inputs to the TopNet hydrological model are described. Chapter 3 also outlines the methodology by which the TopNet model for the two catchments was tested, run for a number of flood events, and modified to reflect potential land use change scenarios in the two catchments.

The results of the research project are presented and discussed in Chapter 4, and conclusions drawn in Chapter 5.

2 Literature Review

2.1 Land Use and Land Use Change in New Zealand

This section outlines the past trends in land use and land use change in New Zealand, focussing on agricultural land use and forestry. The historical context and driving mechanisms, the potential for future land use trends, and the effect land use change has had on the hydrology of the affected areas are presented to provide context and background for this research project.

2.1.1 Agriculture

The following subsections describe the historical trends in agriculture and agricultural land use in New Zealand, and describe the effect the industry has on river basin hydrology.

2.1.1.1 Historical Context

Agriculture has been a feature of the New Zealand landscape since habitation by Polynesian settlers some 500 to 750 years ago. This pre-European agriculture was characterised by the burning of lowland forests to clear land for kumara and other vegetable crops (MacLeod & Moller, 2006). Agricultural practices of European settlers prior to the early 19th century looked to harvesting and hunting natural sources, such as birds and fish, which in turn depleted the natural stocks. Pastoralism became more widespread from the 1840s to the 1860s, and in the late 19th century pastoral expansion necessitated extensive cutting and burning of forests and was further encouraged by the adoption of refrigerated exporting in the 1920s. By the early 20th century, pastoral land in New Zealand covered some 2M ha. The period between the World Wars was characterised by agricultural intensification, made possible by advances in early agricultural science (PCE, 2004).

The rate of agricultural development in New Zealand increased in the latter half of the 20th century, and was characterised by intensification and diversification. Increased stock rates and yields, increased fertiliser use, conversion to more intensive forms of agriculture, and diversification into less traditional agriculture fields such as deer and viticulture, were outcomes of diversification and intensification (MacLeod & Moller, 2006). Up to the 1970s, post-war Britain was the main destination for New Zealand agricultural exports. This, combined with advancements in agricultural science and the government support scheme for the farming sector helped the agricultural output of New Zealand double between 1945 and 1970 (PCE, 2004).

Britain's entry into the European Economic Community in 1973 saw a void in the export market, which was filled by expansion in to new, large, competitive markets in Asia and North America. The mid-1980s saw the deregulation of the farming industry and the removal of government subsidies – it has been estimated that in 1984, government subsidies made up 33% of farm income, compared to 2% in 2003 (Smith & Montgomery, 2004). The new competitive export markets and industry deregulation necessitated more efficient and intensive farming for the industry to remain viable, a trend that continues today. In fact, as of 2004 there were approximately 70,000 farms in New Zealand, covering 14M ha – over half of the country's land area (PCE, 2004). Despite new developments in agricultural science, there is debate over whether the rate of agricultural intensification is ecologically sustainable, especially with regard to water and irrigation, and fertiliser and runoff (MacLeod & Moller, 2006). It is commonly acknowledged that, while the current state of New Zealand agriculture is economically strong, the social and environmental impacts of deregulation and intensification were heavy (Smith & Montgomery, 2004).

Historically the most widespread agricultural activity, sheep and beef farming remains significant in New Zealand. It commands the use of approximately three-quarters of all farmland and forms an important export market (PCE, 2004). While sheep and beef stock numbers have decreased by 42% and 13%, respectively, between 1980 and 2003, intensification and advancements in agricultural science have seen national production of sheep and beef products increase. This was a result of increased lambing and calving rates, and significant increases in animal size – 25% increase for lamb, 18% for mutton, and 13% for beef between 1980 and 2003 (PCE, 2004). While producing a lower-value commodity, sheep and beef farming typically requires fewer inputs to the land than dairy farming, such as irrigation and fertiliser.

Dairy farming is now the largest industry in New Zealand, accounting for around 20% of net export earnings in 2004. The industry is also significant on a global scale, with one third of all international dairy trade originating from New Zealand (PCE, 2004). This large and valuable industry has been the subject of rapid growth and intensification, particularly in the latter 20th century and early 21st century, and is expected to continue to grow despite a strong New Zealand dollar discouraging exports (MPI, 2012). The dairy industry has expanded and intensified, with a 12% increase in area farmed and 34% increase in dairy cows from 1994 to 2002, coupled with a 19% increase in dairy cows per hectare. Efficiency has also increased, with production volume per hectare increasing by 34% for the same period

(PCE, 2004). While dairy farming in New Zealand is primarily focused in the North Island, where the climate is more steady, dairy farming is also expanding into the drier regions of Otago and Canterbury through intensive irrigation (PCE, 2004). The use of water resources for irrigation has become a contentious issue and has divided public opinion in the regions.

Deer farming and horticulture are relatively new in New Zealand. While they have shown rapid growth, as of 2002 they occupied 2% and 1% of New Zealand farmland, respectively, and cannot be considered significant sectors of the New Zealand agricultural economy (PCE, 2004).

2.1.1.2 Trends in Water Use and Irrigation

Water for irrigation forms a large and important input to the New Zealand agricultural industry, and the area of irrigated land has almost doubled between 1985 and 2002 – an increase from 260,000 ha to 467,500 ha, and more than doubled again between 2002 and 2010 to an estimated 1.1M ha. In the Canterbury region alone, the area under irrigation increased from 150,000 ha to 290,000 ha between 1985 and 2002, accounting for approximately two-thirds of the national increase (OECD, 2007). As of 2010, the land under irrigation in Canterbury was 680,000 ha, or 63% of the land area of the region. While the extent of irrigation in Canterbury has been significantly higher than the rest of the country, the trend is typical of a nationwide increase in irrigation. Under New Zealand resource management law, resource consent must be granted by a unitary or regional authority to abstract water from surface or groundwater sources. Consent to abstract water for irrigation is only given if the water abstraction and subsequent agricultural land use can be shown to have minimal detrimental effect on the environment and the community (see also Section 2.1.3: Land Use Change in the Context of the Resource Management Act 1991).

In a report for the Ministry for the Environment, Aqualinc (2010) provided estimates of the actual water usage of consented takes, which were estimated to be approximately 65% of the total consented volume, which indicated that consent holders were using less water than they were allowed to. The report showed that nationally, the consented area under irrigation increased from 1999 to 2010 (Figure 2-1), and 76% of the land under irrigation was pasture, although this proportion was higher in the southern and central South Island, and significantly lower in the northern South Island regions of Tasman and Marlborough, where viticulture has been a significant land use. Nationally, 51% of water for irrigation was supplied from surface water, 46% from groundwater, and 3% from surface storage reservoirs (Aqualinc, 2010).

The increase in area under irrigation was coupled by an increase in water allocation. Water allocation across New Zealand nearly doubled between 1999 and 2010 (neglecting water for hydroelectric power (HEP) generation, which has remained steady). The largest increases in water allocation between 2006 and 2010 were in the Canterbury region, with an increase in weekly water allocation of 25M m^3, to remain the largest regional consumer of water by some margin (neglecting water for HEP generation). Proportionally, the largest increases in water allocation between 2006 and 2010 have been in the Horizons region of the southwest of the North Island (51%) and Northland (41%). The only regions to experience a decline in water allocation were the Bay of Plenty and Taranaki (Figure 2-2). The abbreviations used to identify each local government authority in Figure 2-1 and Figure 2-2 are defined in Table 2-1.

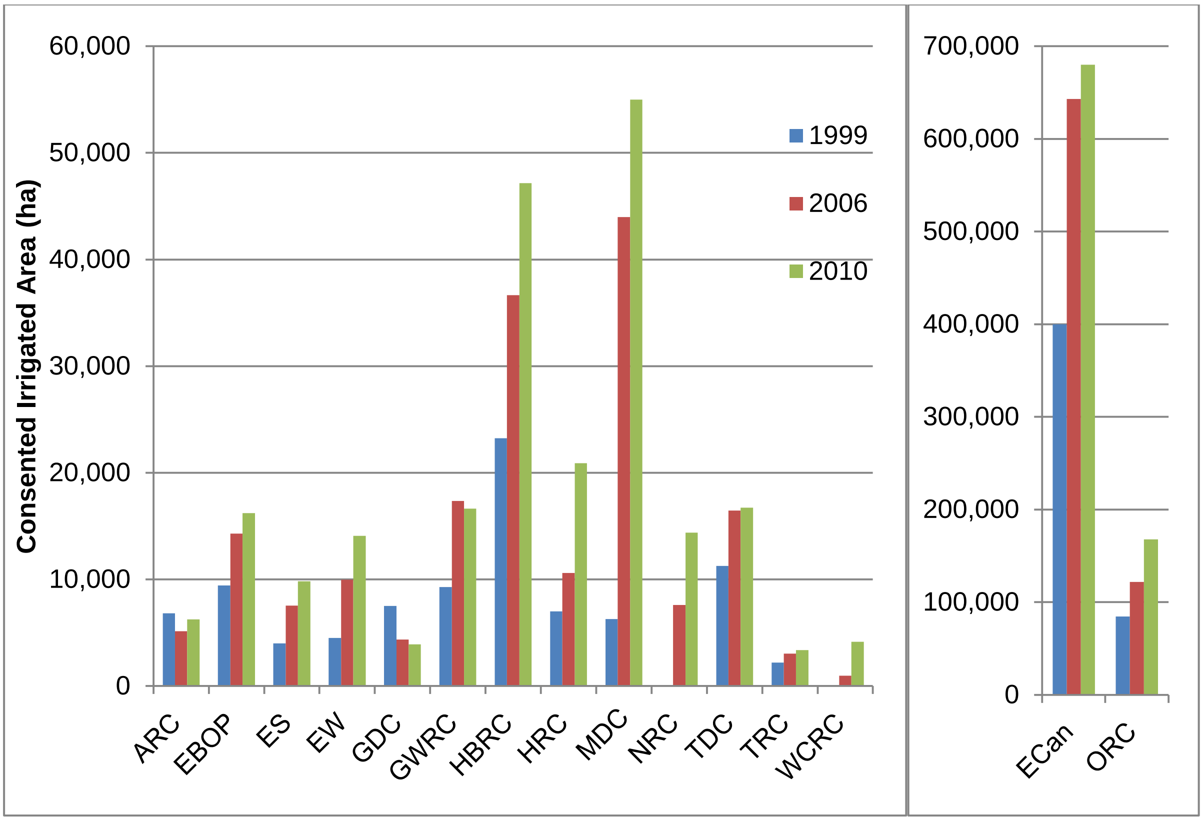


Figure 2-1: Consented irrigated area (ha), 1999, 2006, and 2010 (Aqualinc, 2010)

Note: NRC's 1999 data is omitted due to poor estimates from that year (acknowledged by Aqualinc).ORC data includes 80,000 ha and 108,000 ha supplied from mining water rights in 2006 and 2010, respectively.

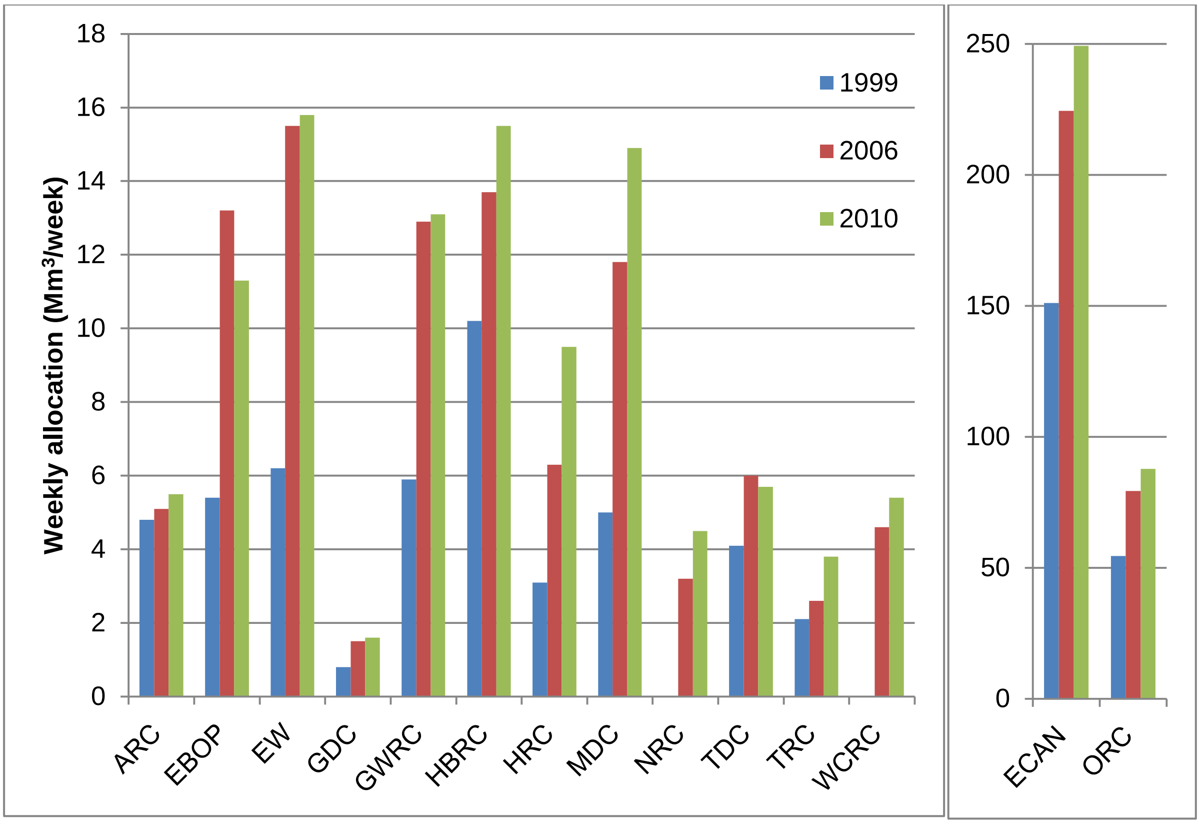


Figure 2-2: Regional weekly consumptive water allocation trends (Aqualinc, 2010)

Note: Trends for Environment Southland have been omitted as allocation for hydropower generation makes up approximately 99% of allocation. Total allocation for Environment Southland was 309.9 Mm^3/week, 312.9 Mm^3/week, and 312.9 Mm^3/week, for 1999, 2006, and 2010, respectively. This is a significant allocation, and is the largest regional allocation in New Zealand, but given a mere 1% is for purposes outside HEP, it has been omitted.

Table 2-1: Abbreviated and full-length names of local government authorities in New Zealand

Abbreviated Name of each Local Authority	Full-length Name of each Authority
ARC	Auckland Regional Council
EBOP	Environment Bay of Plenty
ES	Environment Southland
EW	Environment Waikato
GDC	Gisborne District Council
GWRC	Greater Wellington Regional Council
HBRC	Hawkes Bay Regional Council
HRC	Horizons Regional Council
MDC	Marlborough District Council
NRC	Northland Regional Council
TDC	Tasman District Council
WCRC	West Coast Regional Council
ECAN	Environment Canterbury
ORC	Otago Regional Council

The majority of water abstraction in New Zealand has been for irrigation – some 75% of all water abstracted was for agricultural use, giving New Zealand one of the highest levels of the OECD member countries. If the current trends in global demand for dairy products and other high input agricultural commodities continue, it can be expected that the demand for freshwater resources for irrigation will increase, and the rate of land use change from low input pasture to irrigated pasture may also increase (Aqualinc, 2010). However, the allocation of water abstraction consents has already put pressure on the freshwater resources of New Zealand. The water level of a number of artesian wells in the Canterbury region was measured and water levels were found to be below average in almost all cases, indicating that abstraction of freshwater at the current rate may be unsustainable. This has been a common occurrence across New Zealand, but particularly on the east coast of the South Island (ECan, 2009). Such conditions are likely to result in a reduction in the number of consents issued or reissued and a need for more sustainable management of freshwater resources.

Advancements in irrigation practices have made intensive agricultural activities such as dairy farming a viable land use in semi-arid regions of New Zealand, such as the Waitaki Basin and the Clutha River catchment on the eastern side of the South Island’s main divide. Large irrigation schemes, such as the Upper Waitaki Irrigation Scheme to irrigate pasture in the Hakataramea catchment, and a large number of smaller schemes allow water from the Waitaki Basin to irrigate a total area of 54,600 ha as of 2006, although approximately 85% of this is located in the lower reaches of the basin. Several additional irrigation schemes are expected to add at least 10,000 ha of additional irrigated pasture in the lower Waitaki Basin, and plans to abstract water from Lake Ohau and Lake Pukaki are expected to increase the irrigated area in the upper reaches of the basin (WCWAB, 2006). Dairy farming commands most of the water for irrigation in the Waitaki Basin, and although the dairy industry is a valuable and significant part of the New Zealand economy, the extensive conversion of land from low-input sheep and beef farming to high-input dairy pasture in the basin has attracted controversy, and is expected to continue to do so (Addison, 2009).

2.1.1.3 Effects on Hydrology

While conversion of unmanaged land to pasture has been extensive across New Zealand, research into the hydrologic effects of such activities appears to be fairly limited. More research has been conducted on the effects of afforestation of pasture, and results of such studies may be applicable to the conversion of forested or unmanaged catchments to pasture with the effects reversed. Such studies are referred to in Section 2.1.2.2: Effects on Hydrology. Some research has been conducted in catchments outside New Zealand on the effects of clearing forest and other land cover for pasture. Studies in the 1920s and 1930s found that a watershed in California, USA yielded significantly more water once cleared of its natural forest cover by burning. Similarly, the conversion from juniper (a coniferous evergreen) to grass in 1966 resulted in a 10% increase in runoff from a Beaver Creek, Arizona catchment (Reid, 1981). The differences in water yield between different stages of forestry and the conversion of forestry to pasture have been attributed, in part, to differences in interception, throughfall, evapotranspiration, and the influence on infiltration, and similar trends can be found in the observation of hydrologic behaviour before and after the harvest of plantation forestry (Fahey, Duncan, & Quinn, 2004). There has been very little work done on assessing the effects of converting tussock grassland to pasture in mountainous environments, although such a change has occurred in the high country of the South Island and remains a potentially significant future land use scenario. In theory, converting tussock to pasture may increase transpiration, which could reduce water yield, although this has not been thoroughly tested (Fahey & Rowe, 1992).

Irrigated pasture can display different hydrological characteristics to low-input pasture and grassland. Hence, conversion to irrigated pasture from tussock grassland or forest, or the commencement of an irrigation scheme on previously unwatered pasture may influence the hydrology of the affected area. Irrigation can influence the antecedent moisture conditions in soil such that properties such as hydraulic conductivity K_S are increased (Rowe, Fahey, Jackson, & Duncan, 1997). While this may increase conditions conducive to saturation excess runoff, some studies have suggested that this effect may be insignificant (Rowe, Fahey, & Jackson, 2002). Furthermore, hydraulic conductivity may be more influenced by temporal variation in soil chemical properties, vegetation root systems, and seasonal cycles (Gonçalves et al., 2007; Mubarak et al., 2009). The current irrigation systems may be limited by their efficiency. A study of the hydrological impacts of irrigated agriculture in the Mahuherikia catchment, Otago, demonstrated a significant and unavoidable water loss under irrigation, despite attempts to manage and optimise the scheme using climate and soil moisture monitoring. The inevitable losses were attributed to increased actual evapotranspiration, deeper rooting systems relative to natural land cover, the nature of the hydrological conveyance system, and application losses (Kienzle & Schmidt, 2008).

The engineering structures associated with irrigation and river engineering can reduce the flood hazard of extreme precipitation events. The erection of dams and control structures and the constriction of reservoirs has been shown to reduce the impact of extreme events, provided they do not exceed the level of design of the engineering measures (Griffiths & Ross, 1997).

2.1.2 Forestry and Harvest

The following subsections describe the historical trends of forestry in New Zealand, with particular focus on the upper South Island, and describe the effect the forestry industry has on the hydrology of a catchment.

2.1.2.1 Historical Context

The modification of forested landscape and the forestry industry have been a feature of the New Zealand landscape since early Polynesian settlement, where natural forest was generally cleared by burning. This practice was also employed by European settlers up to the late 1800s, as well as the harvest of mature native hardwood species. 1919 saw the establishment of the State Forest Service with the intent to regulate and manage the growing forestry industry, the cornerstone of which was exotic pine species. The establishment of the State Forest Services facilitated the first planting boom, which satisfied lumber demand up to the 1960s. Increased demand for timber encouraged widespread planting again and could be considered the second forestry boom, which was coupled by technological developments and increased awareness of the environmental effects of plantation forestry. The establishment of the Soil Conservation Authority in 1942 and research into high-country forestry management helped to improve the efficiency of the forestry industry in New Zealand and opened up new landscapes for plantation. The third planting boom in the 1990s was facilitated by increased export demand for lumber. It was generally characterised by the conversion of grassland and pasture to forestry, rather than clearing native forest (Colley, 2005).

In the early 21st century, forestry harvest was at its highest historical level, primarily due to the second and third plantation booms in the 1960s and 1990s, respectively. While the New Zealand Institute of Forestry acknowledged that current plantation trends were down slightly on past years, the industry has been expected to grow again as demand for forestry products increases and forestry becomes more attractive under recent environmental legislation put in place in the wake of the Kyoto Protocol, which encourages carbon sequestration and the reduction of net carbon emissions by each signatory nation (Colley, 2005).

As of 2004, plantation forestry accounted for 7% of the land area of New Zealand, a total of 1.8 million hectares (Colley, 2005). In 2001, the forestry market was worth approximately $2.8 billion, or 4% of the GDP of New Zealand, however it was expected to triple between 2001 and 2025 (Edlin, 2001). In the year ending March 2012, forestry exports totalled $4.3 billion, an increase on 53% from 2001 (MPI, 2012). Radiata pine accounts for some 90% of the exotic plantation forestry in New Zealand, and typically has been planted below an elevation of 800 m ASL in areas that experience greater than 600 mm rainfall annually. Douglas fir, a much smaller crop, can be found at higher altitudes (Fahey, Duncan, et al., 2004). Reforestation of native forest and scrub such as manuka and kanuka has become an attractive alternative to exotic forestry for carbon sequestration. As understanding of the methodology of carbon farming grows, it can be expected that reforestation of native vegetation will become more common (Funk, 2009).

2.1.2.2 Effects on Hydrology

The forestry industry is a dynamic land use that changes the surface cover and consequently the hydrological behaviour of the land throughout the forest lifecycle. The land cover can range from bare cleared land following the clearfelling of trees to mature exotic tree cover, and planting, growth, and harvest can cause rapid changes to the land cover and the hydrology of an area. Given the significant effect they may have on an area, in most cases each stage of the forestry process, such as planting or harvesting, requires land use consent from the unitary or regional authority to ensure the adverse effects of the processes are limited (Fahey, Duncan, et al., 2004). Land use consent may be granted after it can be demonstrated that measures will be taken to ensure the effects on the environment and community are minimised. This may include engineering temporary works such as roads, culverts, and sediment settling ponds, and scheduling work to minimise the impacts of noise, dust, and disruption to traffic (NRC, 2012).

The effects of deforestation and afforestation on basin hydrology have been explored in some detail. Radiata pine may intercept up to 23% of precipitation. When frequently wetted, canopy evaporation may be responsible for up to 70% of total evaporation losses (Fahey, Duncan, et al., 2004). Evapotranspiration from radiata pine forests can remove up to 42% of gross annual rainfall, particularly in drier climates such as on the Canterbury Plains, and intercept between 20% and 29% of rainfall (Fahey, Watson, & Payne, 2001). Many studies have shown that afforestation can significantly reduce the water yield of a catchment. Conversely, deforestation and forestry harvest can increase water yield. The hydrologic effects can be difficult to quantify and depend heavily on the distribution of rainfall and other hydro-geological variables (Fahey, Duncan, et al., 2004).

A study by Smith (1987) showed that an afforested catchment in East Otago yielded 43% less water on average, and generated smaller storm flows than a grass-covered catchment. The difference in yield was proportionally larger for a larger rainfall event, which suggested that the ability of radiata pine forest cover to intercept precipitation relative to grass cover increased with increased precipitation. A similar study showed that the reforestation of a pastured catchment in the Mangatu Forest, Gisborne, reduced annual runoff by 30% (Pearce, O'Loughlin, Jackson, & Zhang, 1987).

Fahey (1994) explored the effect of plantation forestry on water yield in New Zealand through a number of experimental catchments. The study found that afforestation of pasture reduced water yield in the catchment by between 30% and 50% in the first five to ten years after planting. The study also found that low flows were reduced by between 30% and 50%, and peak storm flows reduced by over 50%. Conversely, harvest and clearfelling of forest caused a 60% to 80% increase in water yield across a catchment in the first three to five years, and mean annual floods increased by up to 50% (Fahey, 1994).

A comparative study of topographically similar catchments near Moutere, Nelson, showed that the peak discharge from the pine-afforested catchments was 20% of the peak discharge from the pastured catchment during a storm event (Duncan, 1980). In a later study of the same catchments, there was evidence of significant differences in flood characteristics: the mean annual flood from the pine catchments was found to be 35% of the magnitude of the mean annual flood of the pasture catchments. The 50-year flood event from the pine catchments averaged 50% of the flood in the pasture catchment (Duncan, 1995). The study also suggested that, for the specific catchments, the differences in flood flow characteristics were due in part to differences in soil moisture between catchments. In the past such differences had often been considered negligible, with slope and vegetation cover considered more significant (Fahey, Duncan, et al., 2004). A more recent study based in the Glendhu Experimental Catchments in Otago showed that afforestation reduced catchment runoff substantially: a 7-year-old established forest reduced runoff by 260 mm/year, primarily due to increased interception (Stewart & Fahey, 2010).

While the effects of afforestation on hydrology in New Zealand have been studied extensively, there have been limited New Zealand-based studies for assessing the effects of harvesting and clearfelling plantation forestry. However, this harvesting is analogous to the clearing of native forest (Fahey, Duncan, et al., 2004). The clearing of a beech forest at Maimar, Reefton, resulted in a maximum increase in water yield of 76% (Rowe & Pearce, 1994). Clearing of a similar forest at Donald Creek, Nelson, resulted in an average increase in water yield of 61% across three years (Fahey & Jackson, 1997). The harvest of the Glenbervie Forest, a radiata pine forest near Whangarei, resulted in an immediate increase in water yield of approximately 75% (Rowe, 2003).

International studies across a wide range of catchments have also shown that forest cover can reduce runoff, in some cases by a significant amount. A study following the logging and regeneration of a forest in Western Australia found that forest harvest resulted in increased groundwater levels and increased streamflow. Streamflow increased by up to 18% in the first year following the harvest. The regeneration of the forest after replanting encouraged a return to the previous hydrological behaviour (Bari, Smith, Ruprecht, & Boyd, 1996). A detailed study into the hydrological effects of clearcutting in the Chilean forestry industry also concluded that such a land use change can increase runoff. After clearcutting 79% of a catchment, mean annual runoff increased by 110%, and mean peak flood flows increased by up to 32% (Iroumé, Mayen, & Huber, 2006).

A study by Jones and Grant (1996) attempted to quantify the long-term effects of clearcutting and road construction in small and large basins in Oregon, USA. It was found that harvesting increased peak runoff discharge by up to 50% in smaller catchments, and up to 100% in larger catchments following 50 years of monitoring. Increases in peak flow were measured whenever clearfelling and road construction occurred, and it was concluded that the road and culvert networks contributed to the increase in peak flows. However, the contribution of the road and culvert network was difficult to separate from the contribution from the clearfelling of forestry (Jones & Grant, 1996).

Studies have been conducted into a link between deforestation and increased flooding and flood risk. This link may hold true in the upper Amazon basin: significant deforestation, up to 25% by some estimates, appeared to have had a dramatic effect on the water balance of the upper Amazon basin. While there was no significant change in annual precipitation, the flood peak of the upper Amazon steadily increased as deforestation continued, suggesting a strong link between deforestation and flood peak (Gentry & Lopez-Parodi, 1980). However, the link is subject to debate. Ives (1989) has argued that Himalayan deforestation was not, or at least not entirely, responsible for flooding downriver on the Ganges and Brahmaputra rivers, since Himalayan deforestation has been a feature since the 17th century and significant flooding only more recently. Instead it can be argued that inappropriate land and water resource management was at fault, coupled with dramatic population growth in the Ganges and

Brahmaputra floodplains, and in Bangladesh, which occupies the delta and confluence of the two rivers. The link between deforestation and flooding has not been extensively researched in New Zealand, although the scenario of the harvest of plantation forestry may provide similar insights.

2.1.3 Land Use Change in the Context of the Resource Management Act 1991

The RMA is the current overarching legislation for the sustainable management and protection of New Zealand's natural resources. While considered by many to be a pioneering and successful addition to New Zealand law, New Zealand still faces numerous challenges in the sustainable management of its resources, including the management, supply, and allocation of fresh water (Fisher & Russell, 2011). By its very nature, the RMA encourages local management of natural resources, enforceable under the Local Government Act 2002, as opposed to the historical case of central governance. As such, unitary and regional authorities can manage resources independently of each other and central government, often with different approaches but within the framework of the legislation. Such approaches must be outlined in local government plans and strategies. However, guidelines are often developed by central government to assist in meeting the criteria of the RMA, such as ensuring freshwater flows and quality (SKM, 2012).

As an indicative case of how resource management is administered by local governments, land management in the Marlborough, Tasman, and Canterbury regions of New Zealand is typical of land management across New Zealand guided by the RMA. Agricultural development in Marlborough, Tasman, and Canterbury is generally controlled by district plans, more specifically the rural land zoning through district and unitary government, and any water restrictions or management guidelines are in place through regional and unitary government (ECan, 2009; MDC, 2009b; TDC, 2008). Where possible and where sufficient water resources are available, agricultural expansion, agricultural intensification and enhanced productivity is encouraged, although consents from local and regional government are often required for drawing surface and groundwater, clearing land of established vegetation, aerial topdressing, and potential discharges to waterways. While the plans acknowledge the increased baseflow generally associated with pastoral land use, they make little or no mention of increased overland flow and potential flood effects. MDC, TDC, and ECan discourage rural land fragmentation, particularly from productive land uses to unproductive land use, such as low-density residential subdivisions. This is to encourage highly productive land use and preserve rural character.

Forestry activities such as planting, temporary earthworks, and harvesting, typically require a resource consent as they may not be permitted activities under the local government plan. Working under the guidelines set out in the RMA, forestry operators must develop plans and demonstrate knowledge and understanding of what actions must be taken to mitigate the environmental impacts of forestry. These include impacts to streams and waterways, air quality, and local ecosystems. For example, forestry operators may be required to establish a riparian management zone to assist in protecting waterways (NRC, 2012).

Forestry can have a significant effect on the hydrology of a catchment, and different measures can be taken within the limits of the RMA to ensure the adverse effects of plantation forestry are held at an acceptable level. TDC has focussed on limiting the extent of pine plantations. The underlying Moutere gravels have a low water yield, and much of the water allocation in the region is exhausted. As such, further afforestation could be expected to lower water yields below acceptable levels – an unacceptable scenario in the context of the RMA. In some areas, catchment water yield has been reduced by more than an acceptable level. To remedy low water yields, the council attempted to limit plantation forestry to 50% of land title, or that a maximum of half of any block of land may be covered by plantation forestry. This generated opposition from the forestry industry. After lengthy appeals and faced with further evidence of the adverse effects of forestry on water yield, TDC actually increased restrictions in some areas to only 20% forest cover across an individual land title. This resulted in some dense forests being thinned and harvested prematurely to fall in line with the new council regulations, and was an example of the measures that can be taken to ensure sustainable management of resources under the RMA (Fahey, Duncan, et al., 2004).

ECan undertook an investigation to identify ‘forestry-sensitive’ catchments in the region. This included catchments where rainfall was the primary source of streamflow and where significant groundwater resources were lacking. Many of the identified catchments were critical to domestic and agricultural water supply, and many were already at allocation limits. Environment Canterbury determined that any new plantations should not cause a reduction of greater than 5% to the 7-day mean annual low flow, and the guideline for this was set at 10 – 15% afforestation of a catchment for any new forestry operation. This was added to the district plan, although re-planting of existing forests was permitted (Fahey, Duncan, et al., 2004).

It is required under the RMA that any water allocation or land use change does not increase flood hazard. In fact, local authorities, under the power of the RMA and the Local Government Act 2002 are obliged to “control the use of land for the purposes of avoiding or mitigating natural hazards [such as floods]” (Griffiths & Ross, 1997, p. 162). However, it appears that the risk of flooding and the occurrence of flood-related disasters have increased in New Zealand. This has been attributed primarily to increased infrastructure development and population growth within river floodplains, which is in part due to a relatively high level of acceptable flood risk allowed under the current regulatory framework (Smart & McKerchar, 2010).

While it has been considered a successful addition to New Zealand law, in some cases perceived ambiguity in the RMA has been responsible for controversy over the allocation of water between different stakeholders. Such was the case in the Waitaki Basin, where disputes over water resources between the newly-formed HEP company Meridian Energy and irrigation consortiums such as the Aoraki Water Trust in the early 2000s were taken to the High Court (Addison, 2009). It was argued that Meridian Energy was allocated more water than it required for HEP generation, but the High Court ruled that the Aoraki Water Trust was not entitled to take water from the Waitaki River system as permitting further water abstraction in excess of previously determined maximum water takes would be in violation of the RMA. Following the disputes and further planned water resource developments that would take a significant volume of water from the lower reaches of the Waitaki River, the Resource Management (Waitaki Amendment) Act 2004 was passed with the purpose of allowing water allocation in the Waitaki Basin to be more fair and consistent with the purpose and principles of the RMA, and to remedy any ambiguity in water allocation between stakeholders. This was done via the establishment of the Waitaki Catchment Water Allocation Board, a new entity responsible for assessing water resource applications and allocations in the catchment, and has resulted in significant irrigation and agricultural intensification in the area (Addison, 2009).

2.2 Rainfall-Runoff Modelling

Hydrologic, or rainfall-runoff, modelling can be used to predict the response of a catchment to a precipitation event or a climate series. Rainfall-runoff models consider many facets of the hydrologic cycle to predict the fate of precipitation, whether it be interception by vegetation, infiltration to the ground, overland runoff, or any other physical phenomena. Hydrologic models also predict the movement of water through the catchment via the stream network, known as channel routing. Rainfall-runoff models can be useful for short-term flood prediction and for modelling extreme events, which can be useful for flood risk planning and mitigation. They can also be used to simulate long-term water balance and catchment water yield, which can be useful for assessing climate change and resource management schemes. Hydrologic modelling is an exceedingly broad topic, with many applications and even more approaches and methods. This section endeavours to provide a concise overview of hydrologic modelling pertinent to this research project.

One of the earliest and simplest models to be widely used was the unit hydrograph. Developed by Sherman (1932), the unit hydrograph was a basic method to determine the runoff hydrograph for a given catchment from a given precipitation event. Put simply, the unit hydrograph described the response of a catchment to a unit depth of precipitation over a unit of time. The units were arbitrary, but were commonly 1 mm, 1 cm, or 1 inch of precipitation, and 1 hour of time (Singh, 2005). The unit hydrograph for each catchment was unique and determined by measured values of precipitation and streamflow. Of course, this lead to shortfalls in the unit hydrograph technique if a catchment had no records of precipitation or streamflow, thus requiring the estimation of a unit hydrograph. Furthermore, the unit hydrograph technique assumed a uniform distribution of precipitation across a catchment, as well as a linear response to varying precipitation intensity (Singh, 2005). Nevertheless, the unit hydrograph has proven to be a useful and simple tool, and has been extensively used for engineering design. More recently, with advances in computing and numerical techniques, the unit hydrograph has become less common and its shortcomings have become more pronounced (Mays, 2011).

Modern catchment models have progressed from the unit hydrograph approach. Estimates for flow can be made across a catchment, rather than a single point at the outflow, and for a range of hydrological conditions, rather than just high rainfall events. Long-term water balance models have become important for managing the effects of irrigation, abstraction, land use change, and climate change. Such models dispense with the simplicity of the unit hydrograph and instead employ relatively complex systems of governing equations that require computational numerical solutions. The models are generally robust, can be made widely applicable, and given sufficient inputs can be very accurate (Ibbitt, McKerchar, & Woods, 2004).

Temporally, a modern model can be described as *continuous*, which models a catchment over a long period of time, or *event*, which predicts the catchment response to a single rainfall event (Mays, 2011). Spatially, models can be described as *lumped*, *distributed*, or *semi-distributed* (Figure 2-3). A lumped model considers the hydrologic properties of the catchment or large subcatchment to be homogenous. A distributed model applies a geospatial mesh to the catchment. Each mesh element possesses a unique set of hydrologic properties based on the physical characteristics of that particular element. A semi-distributed model is somewhat of a compromise between the two – the size and shape of the geospatial elements are determined by physical characteristics, but they are generally much smaller than a catchment or subcatchment, allowing for a more accurate representation of the variation in hydrological properties than a purely lumped model (Mays, 2011).

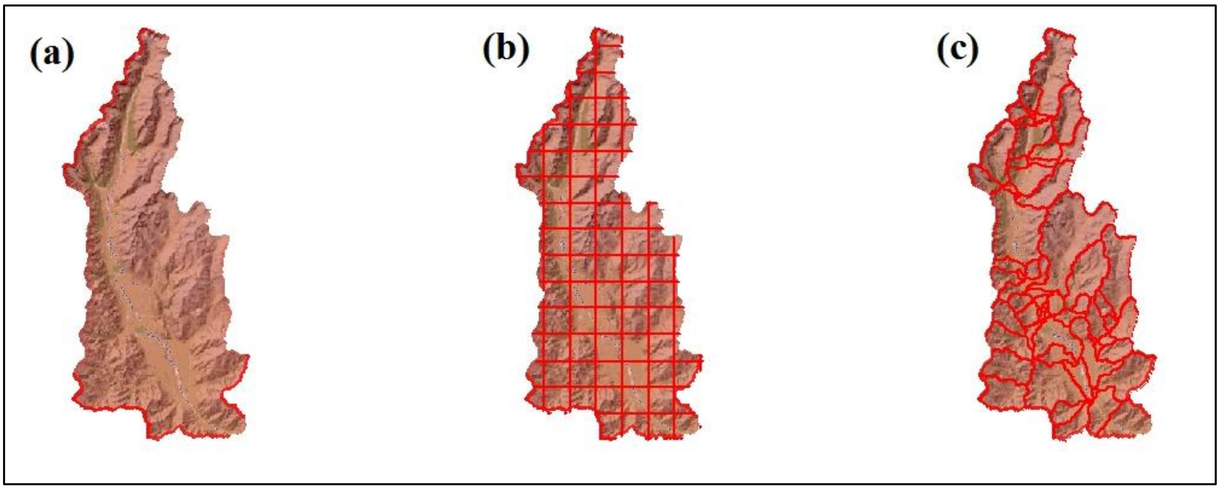


Figure 2-3: (a) Lumped, (b) distributed, and (c) semi-distributed geospatial representation of the Ahuriri River catchment

While there are many modern models in use, they generally possess a similar set of components. Simplified, they are: governing equations that represent processes of the hydrologic cycle, and spatial components that represent the catchment. The spatial components of different models are generally similar, with variations due to catchment area, subcatchment delineation, and geospatial mesh common but not fundamentally different. Developing a set of governing equations to represent the hydrological cycle can be much more complex and varied. The set of governing equations and the processes within the hydrological cycle that are represented depends on the purpose of the model and, ultimately, the approach of the model developer, especially given there is no ‘standard’ for developing a hydrologic model (Ibbitt et al., 2004). There are many ways that hydrologic models may represent physical catchment processes, but some important equations include the approximation of infiltration excess overland flow proposed by Horton (1933) and saturation overland flow first hypothesised by Hewlett and Hibbert (1967). Subsurface flow through the saturated soil matrix is generally described by Darcy's law (Davie, 2004). The Green-Ampt method is commonly used for describing infiltration and was developed using Darcy's Law by Green and Ampt (1911). Curve numbers are a common method of estimating the rainfall runoff from a given depth of precipitation. They were developed by the U.S. Department of Agricultural Soil Conservation Service (SCS) in 1972 to describe the direct rainfall-runoff relationship of a catchment, and depend heavily on soil type and vegetation cover. SCS curve numbers have been used extensively in modelling and water resource engineering applications (Mays, 2011).

As the models become more sophisticated, and more models are developed, it can be difficult to differentiate between models and how well they perform. The distributed model intercomparison project (DMIP) is an example of a comprehensive assessment of modern distributed and semi-distributed models (Smith & Gupta, 2012). The DMIP is a two-phase investigation established by the US National Weather Service to assess the ability of a variety of distributed models to replace the existing network of lumped models for forecasting river operations, water resources, and floods. The models were continuous to enable their use in river operations management and low flow predictions, but there was some focus on peak flow forecasting for flood prediction. The DMIP found that, in general, distributed models can account for spatial variability in a basin while successfully preserving water balance. It was also found that distributed models have the potential to provide improved hydrographs when compared to lumped models. However, the project also concluded that distributed models can be overly sensitive to some model parameters, and that the model developer may have a significant influence on the accuracy of any model (Reed, et al. 2004; Smith, et al. 2012).

2.2.1 The New Zealand Context

Given the heavy reliance of many facets of the New Zealand economy and society on water resources, it is not surprising that a wide selection of modelling packages have been used to develop hydrologic models across the country. The use of models in New Zealand has included engineering design, water resource investigation and quantification, management strategy development, and scientific investigation into new models or model components. While early models were based on the unit hydrograph, more recent models have followed international trends and taken advantage of more complex numerical methods and greater understanding of the physical processes acting in a catchment. While the TopNet model is the focus of this investigation, knowledge of other distributed models in use in New Zealand is important.

The MIKE series of models, developed by the Danish Hydraulic Institute, have been widely applied in New Zealand. The river model MIKE 11 and the integrated catchment model MIKE SHE are distributed hydrologic models (Singh, 1995). MIKE 11 can be used in river engineering applications such as flood analysis, reservoir simulations, and water quality assessments (DHI, 2009). MIKE SHE can be applied to many water resource management scenarios, such as integrated catchment hydrology, surface and groundwater use, and land use and climate change (DHI, 2007). MIKE SHE was developed using the Système Hydrologique Européen (SHE), a physically based spatially distributed system that was designed to model surface and subsurface water resources (Ewen, Parkin, & O'Connell, 2000). The modelling packages are among those recommended for future planning and risk assessment in New Zealand (MFE, 2010). MIKE 11 has been applied in both phases of the DMIP, and MIKE SHE in the second phase. In the first phase of the DMIP, MIKE 11 was applied to only one of the eight basins in the study. The model was found to produce relatively accurate results but a trend could not be established due to its use in only a single test catchment (Reed et al., 2004). In the second phase of DMIP, MIKE SHE was found to display a relatively high cumulative flow error, while MIKE 11 a relatively low error when compared to other distributed models applied to the same catchment (Smith, et al., 2012).

The WATYIELD water balance model was developed as a decision support tool by Landcare Research New Zealand. The model can be used to predict the effects of land use on water yield, but was not designed to predict flood flows. Key outputs include daily flows, soil drainage, stored water, annual water yield, and mean 7-day low flows. WATYIELD can be applied where data pertaining to climate, soil cover, and vegetation is limited, which is a common limitation of modelling New Zealand catchments (Fahey, Jackson, & Davie, 2004). The model has been used in the prediction of catchment water yields and low flows following land cover change scenarios (Fahey et al., 2010). The integrated catchment management programme for the Motueka River, near Nelson, employed WATYIELD as a primary hydrologic model. It has also been used in an attempt to quantify the influence of fog on the water balance in the Glendhu Experimental Catchments in Otago (Fahey, Davie, & Stewart, 2011).

The SWAT model has been used in New Zealand and abroad to assess the impacts of different land management practices on the hydrology of a watershed. The catchment-scale model is run at a daily time-step and can consider large, complex watersheds, a variety of soil profiles, and different land use conditions over an extended time period. As such, the model has been used for long-term, continuous modelling rather than event-based flood prediction (Neitsch, Arnold, Kiniry, & Williams, 2011). The SWAT model was applied to the Motueka River catchment to predict the effects of land cover change on the hydrology of the catchment, including total water yield, storm flow, groundwater flow, and water quality (Cao, Bowden, Davie, & Fenemor, 2009)

The SHETRAN model is a physically-based distributed model with the addition of a sediment transport component and a reactive solute transport component. It was developed by the Civil Engineering Department of the University of Newcastle, United Kingdom, with substantial development funding from Nirex Limited (Ewen et al., 2000). Like MIKE SHE, the model is based on the SHE framework for modelling surface and subsurface flow. The model considers 3D transportation of surface and subsurface runoff, including the transportation of solutes and sediments. It can be considered more complex than conventional 1D and 2D hydrologic models, but also more versatile. SHETRAN has the capacity to model flood flows, but it was not the primary reason for its development (Ewen et al., 2000). The model has been used to model flow, sediment, and contaminant runoff from a pastured hillslope in an experimental catchment near Hamilton (Adams, Parkin, Rutherford, Ibbitt, & Elliott, 2005).

HEC-HMS, developed by the United States Army Corps of Engineers, is freely available and has been used extensively in the USA and abroad. It was developed from HEC-1 and retains many of the modelling principles of the original model. The distributed hydrologic model can be applied to a wide range of catchments and has numerous methods for catchment characterisation, rainfall input, runoff generation, and flow routing (Scharffenberg & Fleming, 2010). It has been used in a number of applications in New Zealand, although it was neither designed for, nor has been extensively tested under, the hydrological conditions found in the mountainous regions of New Zealand (Caruso, Rademaker, Balme, & Cochrane, 2013). Caruso et al. (2013) modelled various flood frequency events in the Ahuriri River catchment, New Zealand, with HEC-HMS and found the model predictions to match statistical estimates of flood magnitude reasonably well. However, smaller events were generally under-estimated and larger events generally over-estimated. HEC-HMS has also been used to predict the effect of land use change on the hydrology of Waikato River tributaries (EW, 2010).

Topmodel, which forms the foundation for the TopNet model, is a conceptual hydrologic model developed by Beven (1979). It attempts to combine the physical theory and detail of a distributed model with the parametric and computational efficiency of a lumped model by means of including a minimal number of model parameters to effectively model the physical processes in a basin (Singh, 1995). The conceptual nature of Topmodel affords the modeller freedom to modify the model and as such there are many versions in existence for a variety of purposes (Holko & Lepisto, 1997). Topmodel has been used to model the Maimai M8 experimental catchments, Tawhai State Forest in Westland (Freer, McMillan, McDonnell, & Beven, 2004).

2.2.2 TopNet

TopNet is a semi-distributed, physically-based hydrologic model developed by NIWA for the purpose of modelling large catchments and networks of subcatchments, generally over a long temporal scale. The development of TopNet involved combining principles of Topmodel with a kinematic wave channel routing algorithm to allow the new model to be more applicable to larger catchments. Incarnations of TopNet have been used in numerous studies and it has been shown to be able to model rainfall-runoff reasonably accurately (Bandaragoda et al., 2004; Iorgulescu & Jordan, 1994; Sun & Deng, 2004).

The TopNet model has been used extensively by NIWA to model New Zealand river catchments and networks, with one aim being the development of a nationwide water accounting system (Ibbitt et al., 2004). TopNet has also been applied to the Rangitaiki River catchment in the central North Island to test model calibration techniques (McMillan & Clark, 2009), and used in a skill assessment of linked precipitation-runoff flood forecasting system based on quantitative precipitation forecasts across the country (Ibbitt, Thompson, & Turner, 2005). The model has been used as part of an assessment of the potential effects of land use change on the flood hydrology of Waikato River tributaries (EW, 2010; Woods, Schmidt, & Collins, 2009). TopNet has been applied to catchments throughout New Zealand, including steep catchments such as the Ahuriri, Pelorus, and Hakataramea River catchments, and large catchments such as the Clutha River catchment, to predict the effect of climate change on catchment hydrology and water yield (Zammit, personal communication, 2012; Khadka, personal communication, 2012).

While the model has been shown to be able to accurately predict runoff over a period of time, it has some known shortcomings. The results of the DMIP showed TopNet to have a tendency to predict the runoff hydrology of large basins less accurately than small basins. Furthermore, the predictions were generally conservative, in that the model was inclined to under-predict flow (Reed et al., 2004). TopNet was designed to model long-term water balance, and while it has been used for flood modelling, examples are infrequent and have not thoroughly tested the model's ability to predict flood flows.

3 Methodology

This section describes the methodology for the research project. Important steps in the methodology included selecting suitable catchments for use in the research project, modifying and applying the TopNet model to reflect potential land use change scenarios, and evaluating the performance of the model.

3.1 Catchment Selection

The selection of suitable catchments for this investigation involved establishing selection criteria to ensure the chosen catchments would be fit for the purposes of this project. The criteria for the catchments were:

- The catchment must have steep or mountainous relief;
- There must be an existing TopNet model developed by NIWA for the catchment, and NIWA must allow the model to be used for this investigation; and
- The catchment or surrounding area must be subject to land use change or potential land use change.

Following these criteria, two suitable catchments in the South Island of New Zealand were identified: the Ahuriri River catchment and the Pelorus River catchment. Both catchments are characterised by steep valleys and, although not necessarily subject themselves, their surrounding environments are subject to land use change. Tussock grassland covers most of the Ahuriri River catchment, and there has been agricultural development to a small extent in the lower reaches of the catchment and more extensively in neighbouring catchments. The Pelorus River catchment is forested and is in a region of intensive forestry development so may be subject to forestry harvest and agricultural development. Critically, NIWA had developed a TopNet model for each catchment as part of an effort to model the catchment networks of New Zealand, and have allowed the models to be used for this investigation.

Important sources of information in making these decisions included the Landcare Research online database (LRIS, 2012), which held detailed slope and topographic maps of New Zealand, and the outcomes of previous studies Caruso (2006), Garr and Fitzharris (1991), and others. NIWA provided information regarding catchments for which models had been developed, and the availability of the models.

The climate of the catchments was considered less important than the aforementioned criteria. Given the TopNet models were developed to represent the physical processes acting in each catchment, the climate of each catchment should not have a significant influence on the usefulness of each catchment model. However, in the context of future land use scenarios, climate is important as it may influence what the land can be used for.

3.2 Study Areas

The following section describes the Ahuriri River catchment and the Pelorus River catchment in some detail. The descriptions extend to the surrounding area as the information and trends regarding climate, topography, land use, and management are generally not exclusive to the study catchments.

3.2.1 The Upper Waitaki Basin and the Ahuriri River Catchment

The Upper Waitaki Basin (UWB, or Mackenzie Basin), located on the eastern side of the Southern Alps straddling the Otago and Canterbury regions of New Zealand (Figure 3-1), is characterised by a system of braided rivers and steep alpine valleys. The UWB has been subject to extensive HEP development, which has dominated water resource management and land use change in the region. The first project was completed shortly after World War One, and most recently a system of canals and HEP stations was constucted in the 1980s linking the reservoirs of Lake Tekapo, Lake Pukaki, Lake Ohau and Lake Benmore. As a whole, the Waitaki Power Scheme generates 1738 MW, approximately 34% of the total hydroelectric power generation capacity of New Zealand (Young, Smart, & Harding, 2004).

Large water resource engineering projects such as dams and canals have significantly changed the flow regimes of numerous rivers in New Zealand, and this is typical of the UWB. Flow regimes and flood events are the driving mechanism behind sediment movement, river floodplain geomorphology, regulation and dispersion of vegetation, and for the most part define the ecology of the river. The flow in the Waitaki River is curbed by the extensive canals and control structures on its tributary rivers and lakes (Young et al., 2004). In fact, immediately after the development of HEP control structures on the Ohau River, the river was reduced to zero flow or only intermittent flow from a previous average annual low flow of 80 m^3/s. This was improved by ensuring a constant baseflow of 10 m^3/s was released from the Ohau storage lake (Mosley, 1992). Despite these small concessions, the UWB has still suffered a loss of 17% of its floodplains and at least 41% of its wetlands since HEP development began (Caruso, 2006). It is clear that HEP development has had a significant effect on the rivers, and by association the sensitive riverine ecosystems of the UWB, which is home to a wide variety of native and endemic plants and animals (Caruso, 2006). However;

the Ahuriri River catchment has not experienced HEP development and retains a near-original flow regime.

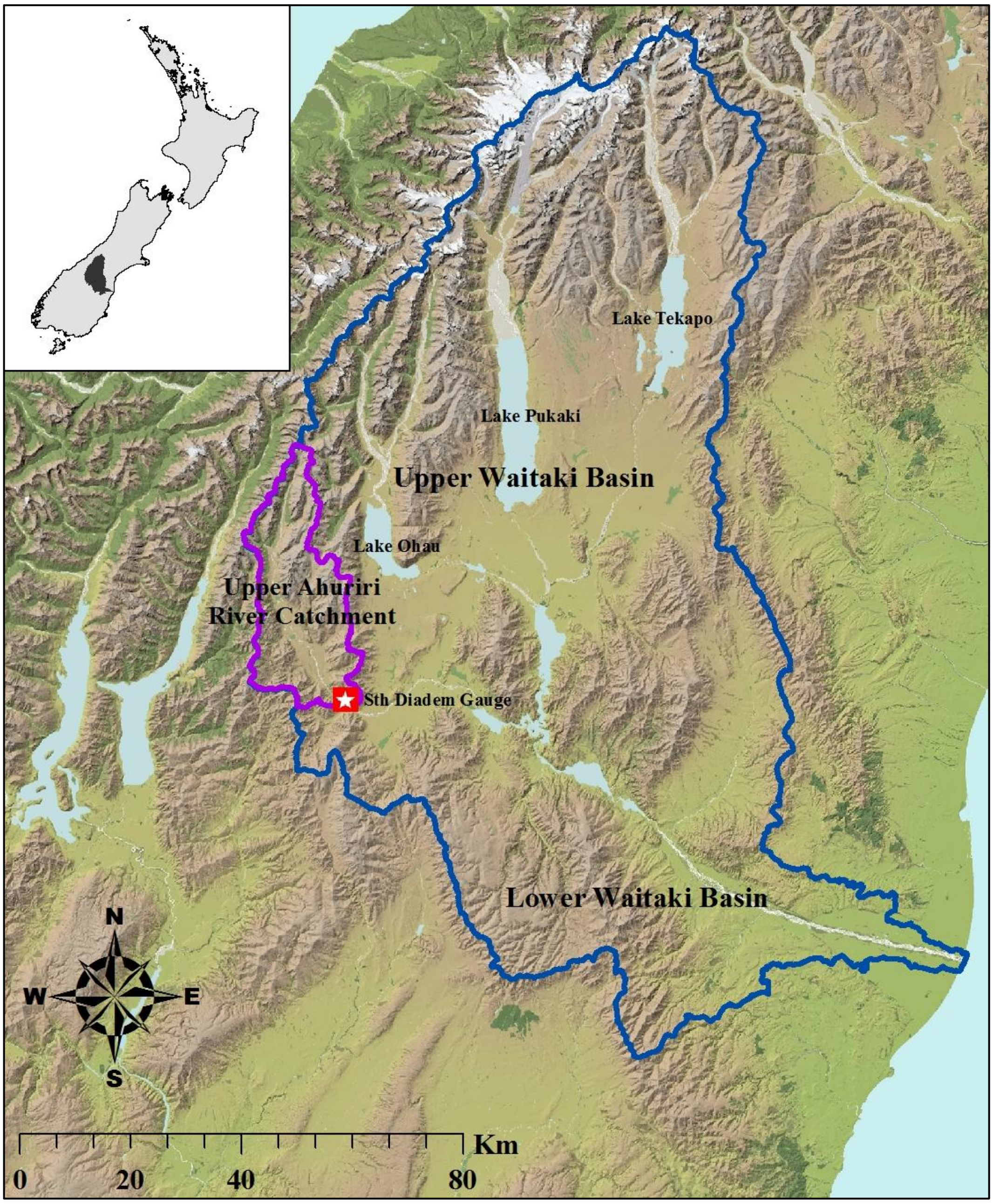


Figure 3-1: Location map of the Ahuriri River catchment and Upper Waitaki Basin

Project River Recover (PRR) was established by the Department of Conservation (DoC) in 1990 in response to the impacts of HEP generation on the UWB freshwater ecosystem. Meridian Energy Ltd, who hold significant water rights in the UWB until 2024, have funded the project through a compensatory funding agreement. The primary aim of the project is to restore and protect the braided rivers and wetlands in the UWB for the benefit of the area's native flora and fauna, and this includes the DoC-administered Ahuriri Conservation Park in the upper reaches of the Ahuriri River catchment. Following an investigation into the effectiveness of PRR, Caruso (2006) concluded that PRR “can generally be considered a good example of a relatively effective habitat restoration program” (p. 919). Caruso also made a number of recommendations to improve the effectiveness of PRR, which included a more detailed evaluation of the flow regimes and hydrology of the rivers in the UWB.

The upper Ahuriri River catchment, located above the South Diadem flow gauge, and which covers an area of approximately 580 km^2, can be considered mountainous, with elevation ranging from 600m ASL in the lower reaches of the catchment to 2500m ASL at Mt Huxley near the main divide. Average annual precipitation ranges from 500mm in the low-lying south of the catchment to 6400mm in the upper reaches at high elevation. The Ahuriri River can experience significant seasonal variation across the year, with the greatest flows in the springtime. The flood season is typically from late spring to mid-summer (Caruso et al., 2013). The average annual flood is 175 m^3/s, based on 45 years of observed data from the NIWA gauging station at South Diadem, and the 100-year flood is 658 m^3/s, based on three-parameter Lognormal and GEV analysis (Caruso et al., 2013). The majority of land cover in the Ahuriri River catchment is tussock grassland, but a significant proportion of the land cover is pasture and exotic grasses used for sheep and beef farming (Figure 3-2). However, only a small proportion of the upper catchment is used for agriculture (Figure 3-3). The land cover in the upper catchment is predominantly tussock grassland, although alpine rock, gravel, and ice are also significant at higher altitude. Figure 3-3 also shows significant agricultural land use south of Lake Ohau, west of the Ahuriri River catchment. As of 2007, there was a small amount of irrigated pasture downstream of the South Diadem gauge in the catchment covering approximately 500 ha. As of 2008, ECan had received applications for approximately 200 ha of irrigated pasture upstream of the South Diadem gauge and a further 500 ha south of the Diadem Gauge (Aqualinc, 2008). The Ahuriri River from its source to the outflow at Lake Benmore is protected by the Ahuriri River Conservation Order 1990, so any water abstraction in the region is unlikely to affect flow in the Ahuriri River (WCWAB, 2006).

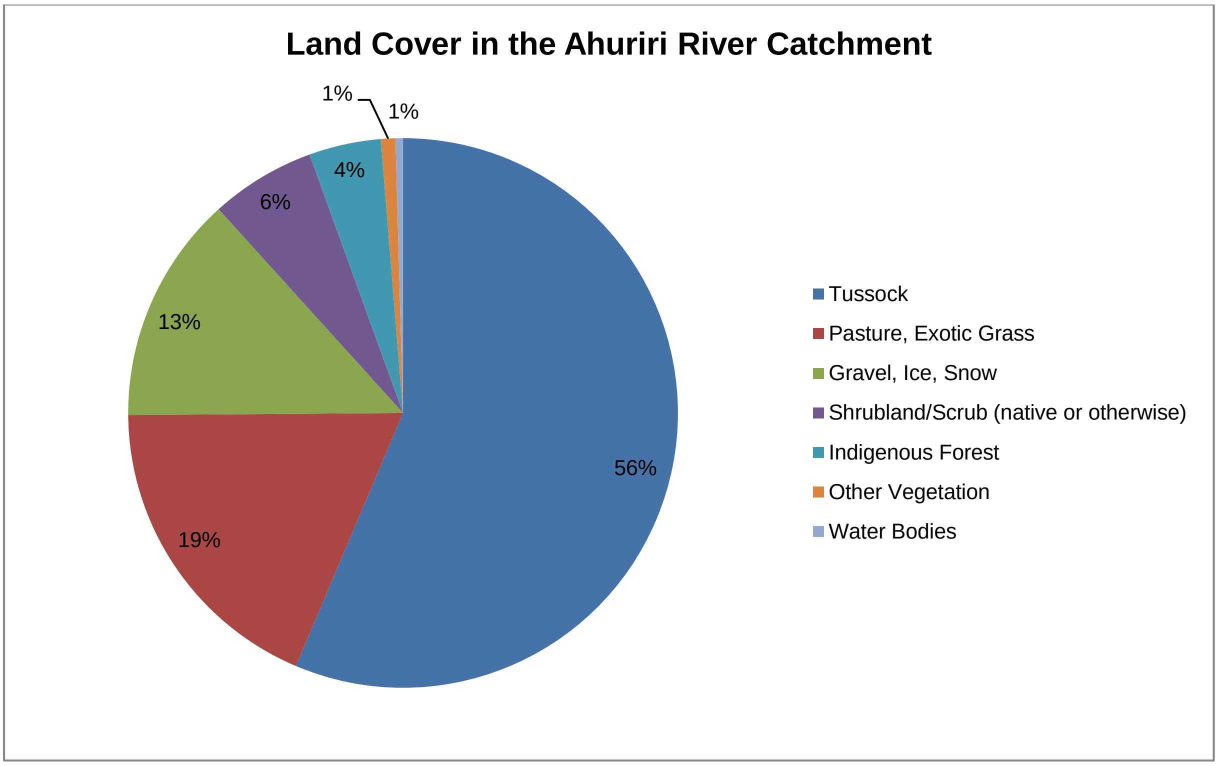


Figure 3-2: Land cover in the Ahuriri River catchment (LRIS, 2012)

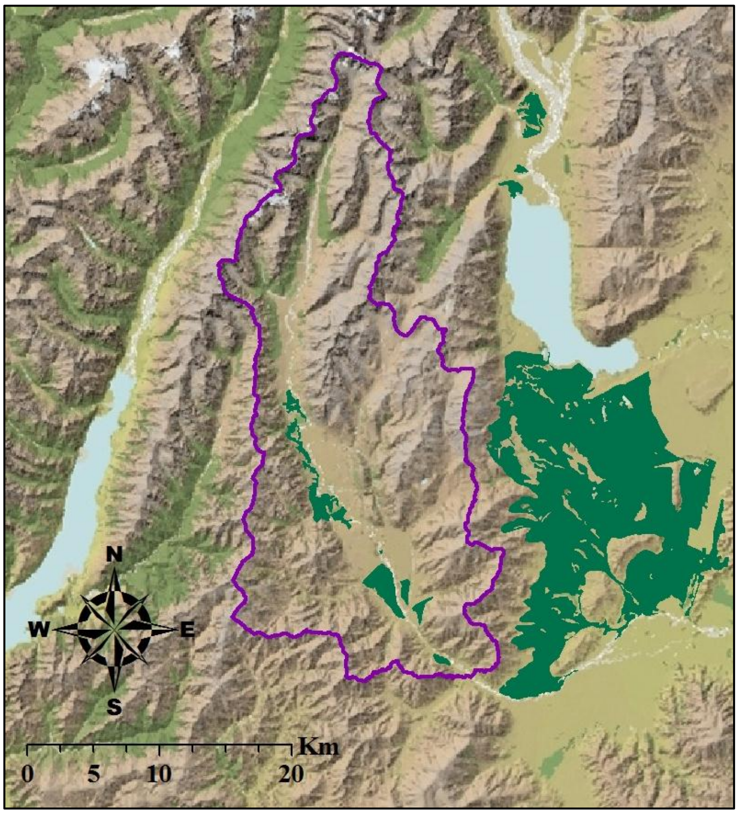


Figure 3-3: Agricultural land cover in the upper Ahuriri River catchment

Some land use change from unmanaged tussock or scrub to agriculture has also occurred in the UWB. Pastoral activities began North Otago in 1848 and soon spread up the Waitaki Basin. The following hundred years were characterised by sheep farming and fluctuating fortunes, with drought, increasing pest populations and water access challenges balanced by times of high wool prices, the development of refrigerated shipping, and advances in agricultural science (Currie, 1974). Of course, agricultural trends in the UWB largely followed national trends, characterised by a movement away from sheep and toward cattle, particularly dairy, and irrigated pasture. In fact, as of 2006 there were 12,600 ha of irrigated land in the UWB, requiring a peak abstraction rate of 15.5 m^3/s from surface and ground water sources and an estimated annual demand of 96M m^3. While the Ahuriri River catchment upstream of the South Diadem gauge has no irrigated pasture, irrigation is significant in some of the other catchments in the UWB. There are significant areas of irrigated pasture for dairy farming downstream of Lake Ohau and Lake Pukaki. As of 2006, there remained up to 80,000 ha of irrigable land in the UWB, which if utilised could increase water demand eightfold (WCWAB, 2006). As of 2008 there were 38 applications for resource consent under consideration by ECan to abstract water from ground and surface sources in the UWB, which would increase the area of irrigated pasture by 17000 ha if all applications were granted consent, the majority of which would be located immediately downstream of Lake Ohau and Lake Pukaki (Aqualinc, 2008). Irrigation schemes take a large amount of water from the reservoir lakes in the UWB. A primary drawback of significant irrigation in the UWB may be a significant reduction in HEP capacity of the Waitaki Power Scheme due to reduced water levels in the HEP reservoir lakes. Under an assumed reduction in power output of 10 – 20%, the economic benefits of increased irrigation would be outweighed by the cost of reduced power output to the national grid (Brown & Harris, 2005). Brown and Harris (2005) also identified social benefits of increased irrigation in the UWB, such as more jobs and population gain in the sparsely populated area. The risk of groundwater and surface water contamination as a result of the intensification of dairy in the UWB was also identified.

Dairy farming in the UWB has developed into a contentious issue. Davis (1996) argued that dairying may provide an excellent opportunity for economic growth in the region. Conversely, Addison (2009) argued that poor planning and insufficient investigation in the UWB has caused ineffective and ultimately unsustainable use and allocation of water resources for irrigation, something that must be improved upon for future agricultural development, in particular the expansion of dairy farming. While there have been numerous measures to encourage sustainable resource use, including the Resource Management (Waitaki Catchment) Amendment Act 2004 and subsequent formation of the Waitaki Catchment Water Allocation Board, Addison argued that the methodology by which water has been allocated was fundamentally flawed. The Waitaki Catchment Water Allocation Plan, which governs allocation in the UWB, appeared to pit the demands of the HEP industry against the agricultural industry, while being somewhat ambiguous with regard to relative importance of each. Furthermore, the legislation surrounding water allocation in the UWB appeared to be more focused on national interest instead of local interest (Addison, 2009). Finally, it can be argued that the allocation plan is based on incomplete and inaccurate hydrologic data. Hence, Addison (2009) concluded that irrigation and dairying, under the current governance, would be unsustainable, and further investigation into the hydrologic characteristics of the UWB would be required to allow improvements to be made to the scenario.

3.2.2 The Upper South Island and the Pelorus River Catchment

The Marlborough and Tasman regions, covering the north of the South Island, have been the setting for a significant proportion of the plantation forestry in New Zealand. Of the total national plantation forestry area of 1,719,000 ha, forestry in Tasman and Marlborough made up 167,000 ha, or 10%, as of 2011. Furthermore, the area has provided some of the most favourable growing conditions in the South Island, with high sunshine hours, mild temperatures, and reliable rainfall. As a result, forestry in the regions makes up one third of the plantation forestry in the South Island, (MAF, 2011). The average age of the clearfelling and harvest of exotic forest in New Zealand was 26.8 years (MAF, 2011). The majority of exotic forestry in the Upper South Island was younger than the average age of harvest as of 2011 (Figure 3-4); hence it is not unreasonable to expect a significant amount of harvest activity in the region in the near future. This is likely to have a significant benefit to the economy of the area, but may also have a significant effect on water yield, flood magnitude, and water quality.

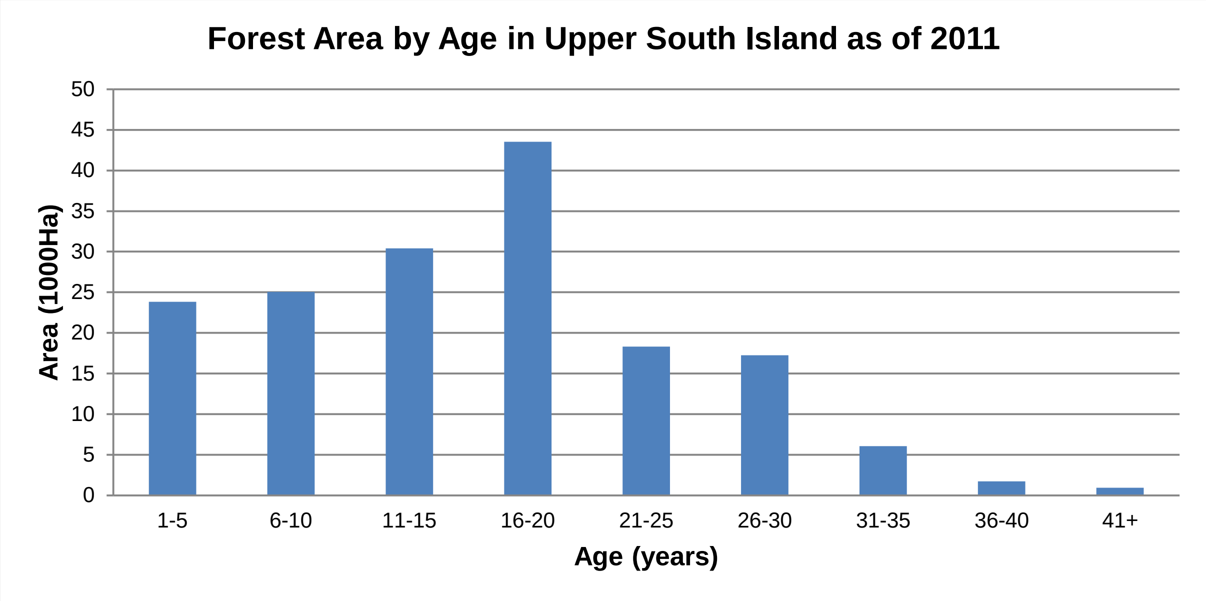


Figure 3-4: Exotic forest area by age in the Upper South Island, as of 2011 (MAF, 2011)

The Pelorus River catchment is located at the northern end of the South Island, in the Marlborough region (Figure 3-5), and drains northeast to the Pelorus Sound at the town of Havelock. While not as extensively studied or intensively managed as the Ahuriri River catchment, the Pelorus River catchment is an important environmental area and as such has been identified by the Marlborough District Council as a ‘significant natural area’, as part of the surrounding DoC-administered Mt Richmond Forest Park. The upper Pelorus River catchment, which covers an area of approximately 380 km^2, is characterised by steep hill-country and mountains that give way to open valley floors. Indigenous forest makes up 89% of the land cover of the catchment (Figure 3-6), and this is typically coupled with a dense undergrowth. A small area of pasture and plantation forestry is located near the downstream end of the catchment (Figure 3-7). The climate can generally be considered mild, and precipitation reliably falls between 1600 mm and 2000 mm annually (MDC, 2009a). The upper Pelorus River catchment ranges in elevation from approximately 40m ASL at the Pelorus Bridge to 1760m ASL at Mt Richmond in the upper reaches of the catchment. There is a gauging station operated by NIWA at the Bryants site (Figure 3-5). The average annual flood of the Pelorus River is 919.9 m^3/s (Horrell, McKerchar, Griffiths, & Griffiths, 2012) and the 100-year flood is 2340 m^3/s based on the Generalised Extreme Value (GEV) statistical distribution developed for this research project (Figure 3-10).

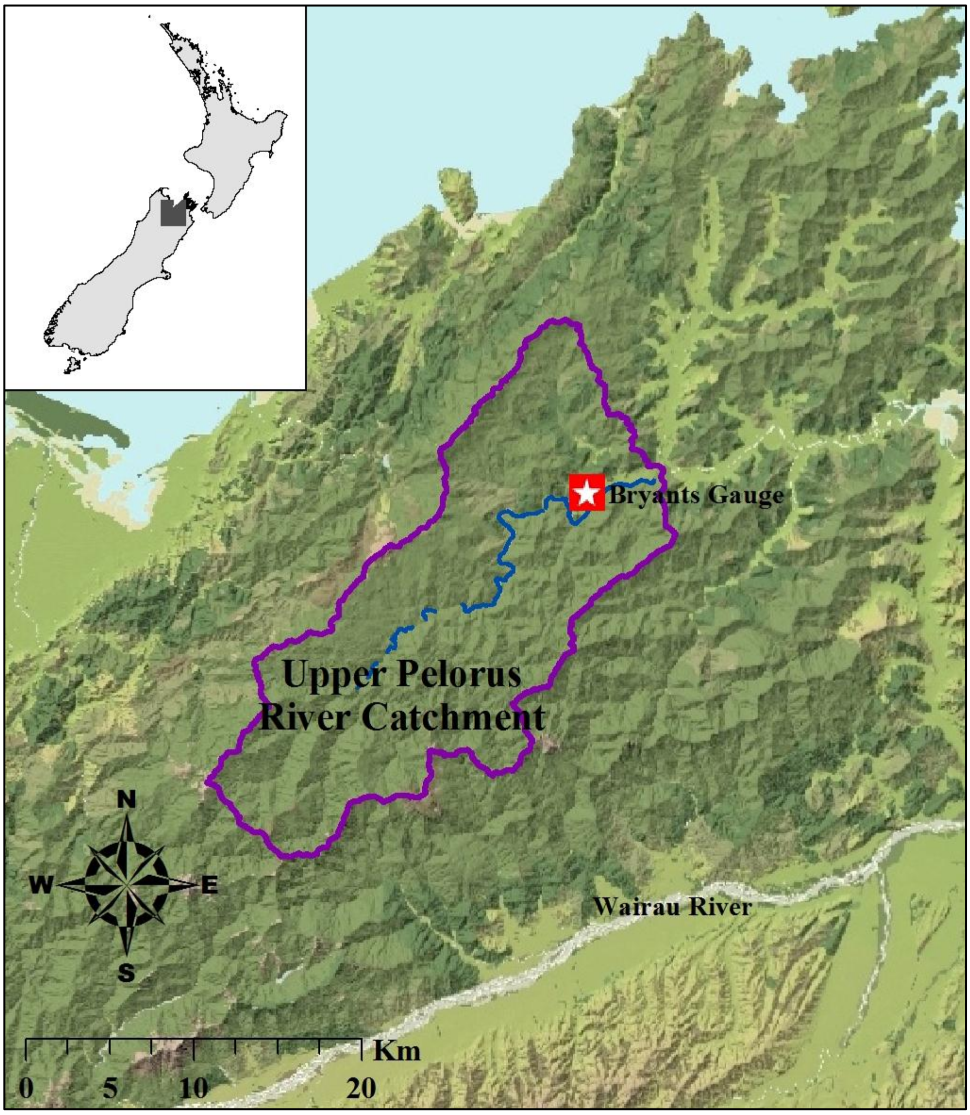


Figure 3-5: Location map of the upper Pelorus River catchment

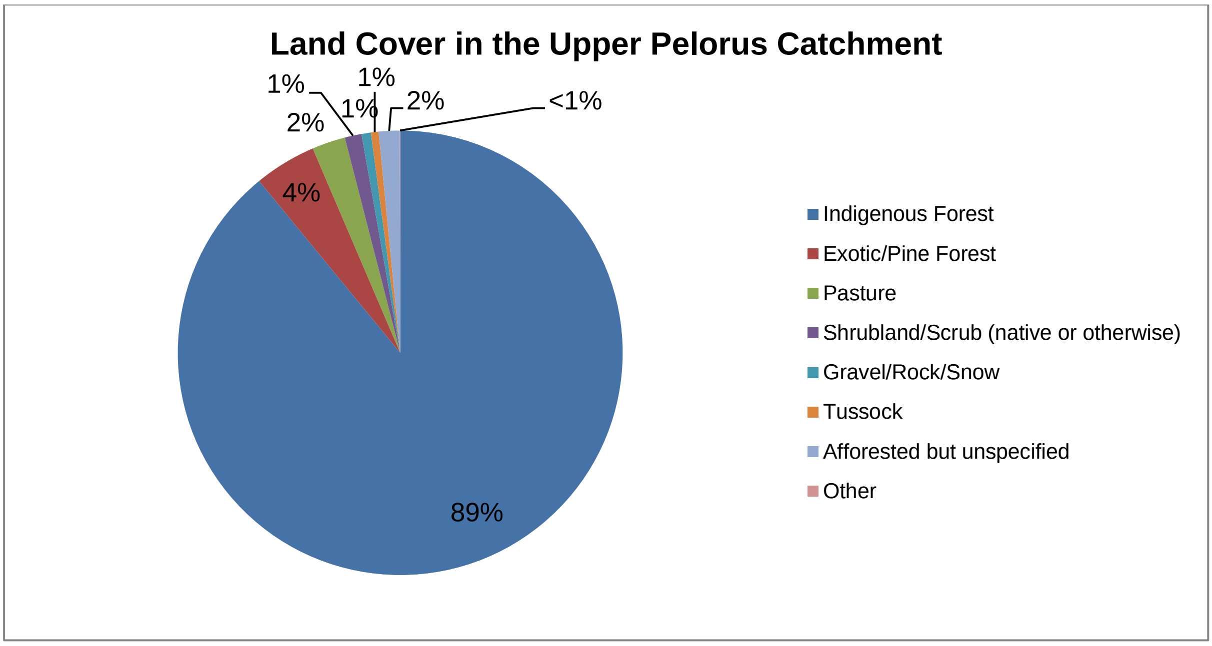


Figure 3-6: Land cover in the upper Pelorus river catchment (LRIS, 2012)

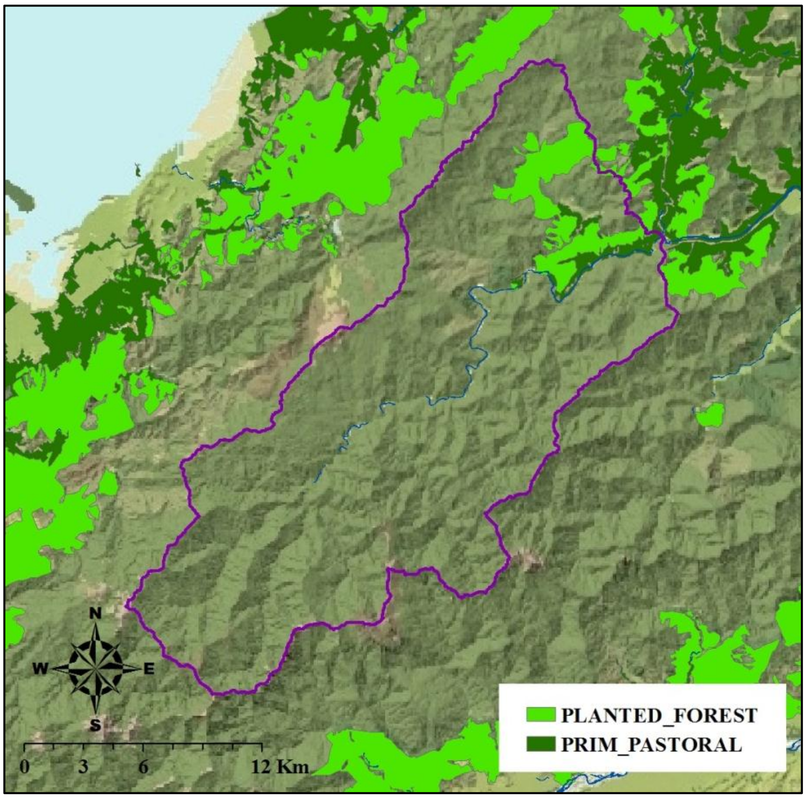


Figure 3-7: Planted forestry and primary pastoral land cover in the upper Pelorus River catchment

Note: The remainder of the land cover in the upper Pelorus River catchment is almost entirely native forest (Figure 3-6)

3.2.3 Comparison of Hydrological Characteristics

The Ahuriri River catchment and the Pelorus River catchment can be considered, in general, to be steep catchments (Figure 3-8). Three key differences can be found in:

- Elevation: The Ahuriri River catchment ranges from 600 m ASL to 2200 mm ASL, while the Pelorus River catchment ranges from near sea-level to approximately 1760 m ASL. Despite this difference in elevation, the relief within the catchments are similar (Figure 3-8), and both are dominated by relatively steep terrain.
- Precipitation: The Ahuriri River catchment experiences significantly more variation in precipitation distribution, with average annual values ranging from 6400 mm in the upper reaches to 500 mm at lower elevations. According to the Marlborough District council, the Pelorus River catchment reliably receives between 1600 mm and 2000 mm across the catchment, although the catchment appears to lack precipitation gauges so precipitation is more uncertain.
- Climate and Land Cover: The Ahuriri River catchment can be considered semi-arid, and the land-cover is primarily tussock and scrubland, while the Pelorus River catchment is more temperate and is generally forested.

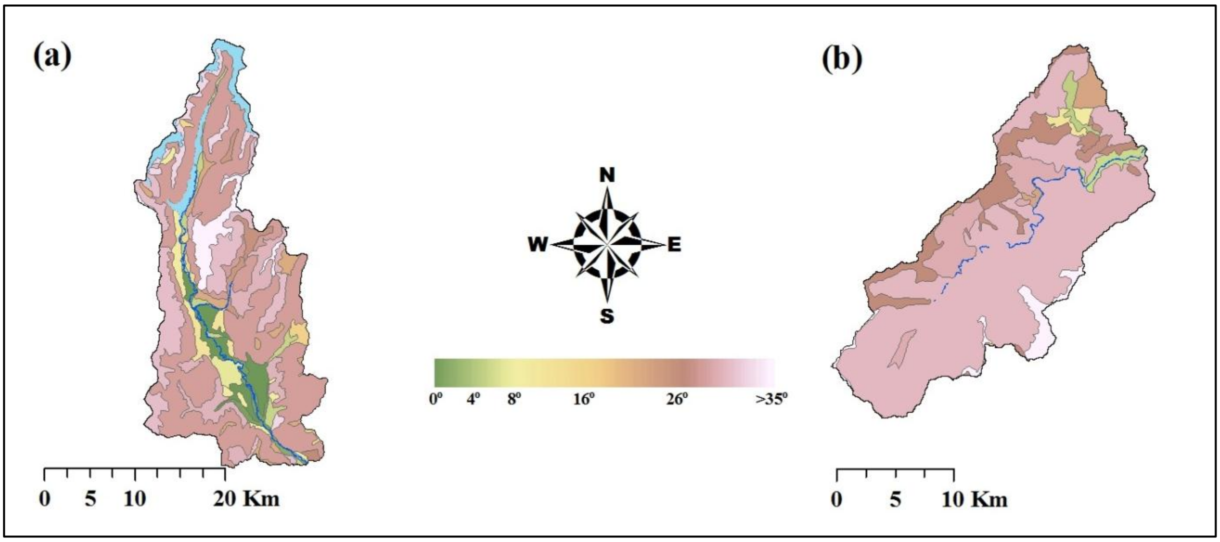


Figure 3-8: Map showing slopes within the (a) Ahuriri and (b) Pelorus River catchments (LRIS, 2012)

High flow events on the Ahuriri River have been found to be well-modelled by the Lognormal distribution and the GEV distribution (Figure 3-9), and Caruso et al. (2013) suggested that taking an average of the Lognormal distribution and the GEV distribution would model floods in the Ahuriri River effectively. However that may not be necessary up to the 100-year event since the two distributions appear to be near-identical (Figure 3-9). A number of studies have suggested that the GEV distribution is a widely applicable to New Zealand rivers (Pearson & Henderson, 2004). The GEV distribution performed well when applied to the flood records for the Pelorus River (Figure 3-10). The parameters for each distribution are presented in Table 3-1. The Pelorus River experienced significantly higher flood peaks than the Ahuriri River despite a smaller catchment area. This may be a result of rainfall distribution in space and time, channel properties such as bathymetry and roughness, and soil properties.

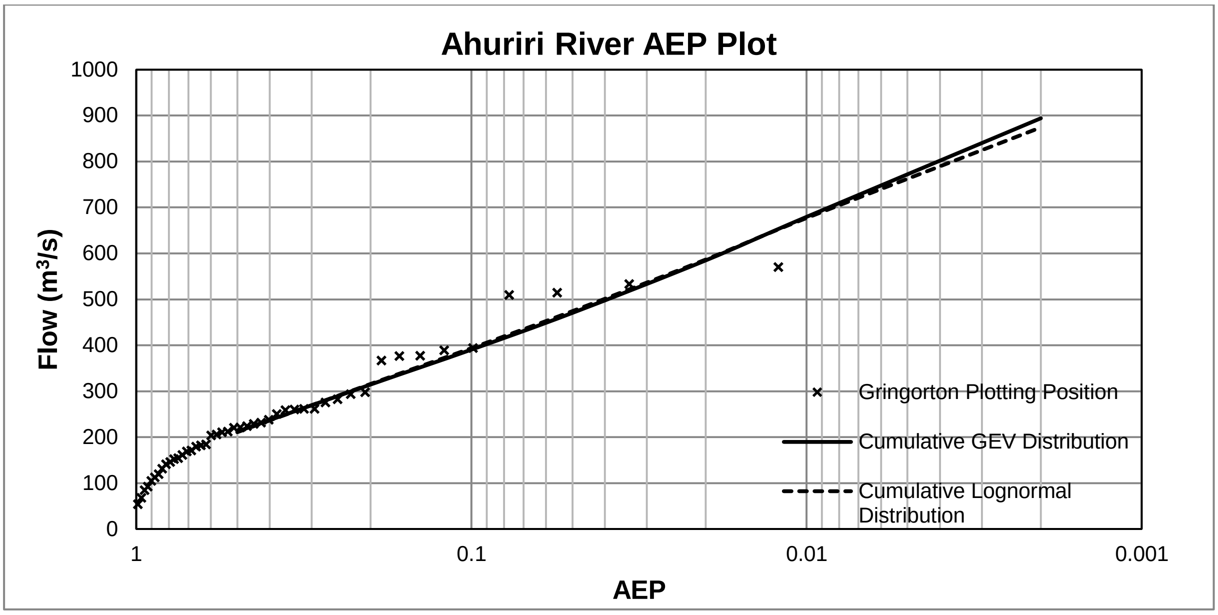


Figure 3-9: Annual exceedance probability (AEP) plot of flood magnitudes for the Ahuriri River (Caruso et al., 2013)

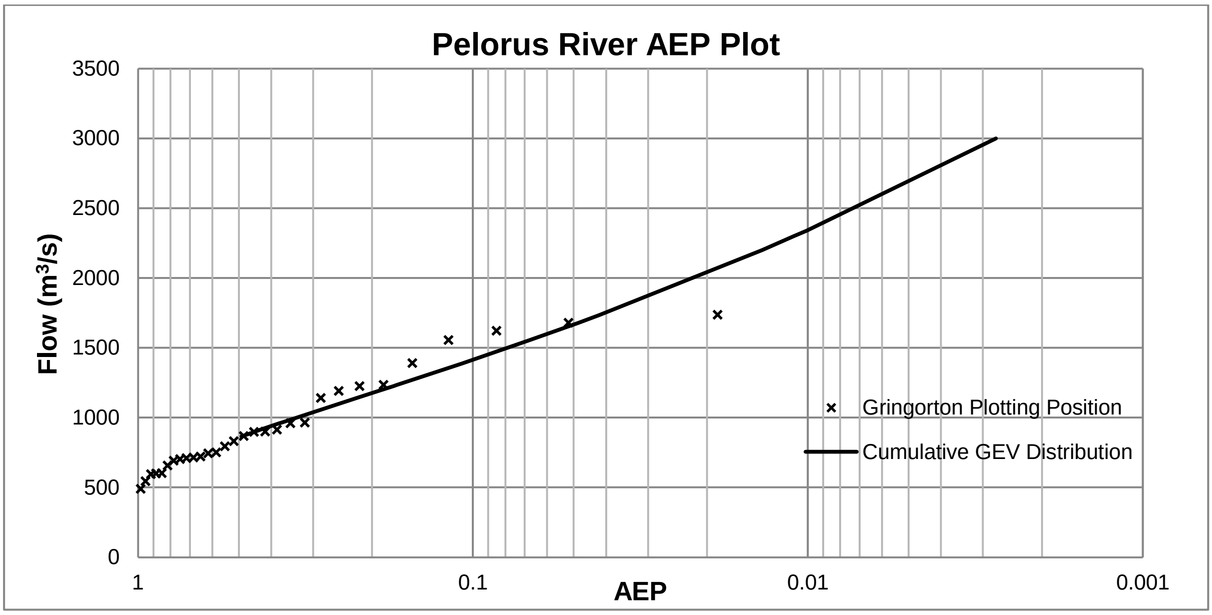


Figure 3-10: AEP plot of flood magnitudes for the Pelorus River developed for this research project

Table 3-1: GEV and 3-Parameter Lognormal distribution parameters for the Ahuriri River and the Pelorus River

Distribution	GEV			3-Parameter Lognormal		
Parameter	Shape k	Scale σ	Location μ	Shape σ	Scale μ	Location γ
Ahuriri River	0.056	92.40	181.6	0.42	5.58	47.28
Pelorus River	0.137	245.8	766.3	-	-	-

Soil properties, such as soil drainage and permeability, may also have an influence on rainfall-runoff generation, although these properties are generally not as significant as rainfall volume and distribution, and catchment slope. The Ahuriri River catchment generally has slightly higher soil permeability than the Pelorus, while soil drainage is similar between the two catchments (LRIS, 2012). This suggests that the Ahuriri River catchment may lose more surface water to infiltration and experience a greater level of groundwater recharge. However, it has been suggested that soil permeability can display significant temporal variation, depending on soil moisture conditions, vegetation root systems, and soil chemistry in the vadose zone (Esling, DeVantier, Zeng, & McDonald, 2000). Hence it is difficult to quantify the effect soil permeability may have on the hydrological response of each catchment to a flood event.

3.3 Description of TopNet Processes

The physical processes approximated by TopNet are shown in Figure 3-11. They can be divided into those that occur within the basin and those that occur throughout the river network. TopNet can also accommodate management scenarios, such as irrigation and reservoir abstraction. Basin processes include: canopy interception and storage; soil storage; infiltration; aquifer and subsurface storage; surface storage; and snowpack storage. River network processes include channel routing and lake and reservoir storage. The following sections define and describe the equations employed to model these processes and outline the key differences and modifications from the earlier Topmodel to develop TopNet.

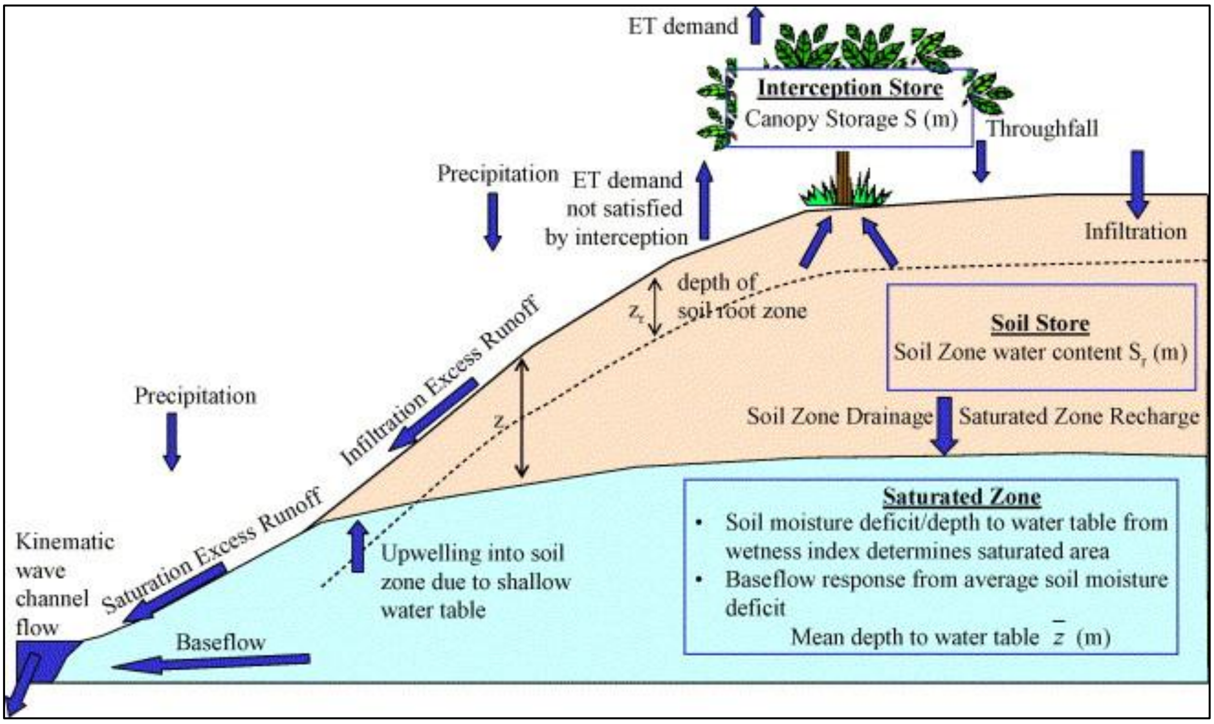


Figure 3-11: Physical processes represented in TopNet (Bandaragoda et al., 2004)

3.3.1 The Evolution of TopNet from Topmodel

TopNet is an evolution of Topmodel, an early distributed model developed by Beven and Kirkby (1979). Bandaragoda et al. (2004) describe the five additional or modified components of the model that allowed for a more holistic representation of physical processes on a larger scale. They are: the potential evapotranspiration component, the canopy interception component, the soil component, the saturated zone component, and the channel routing component.

3.3.1.1 Potential evapotranspiration

TopNet employs the Priestley-Taylor equation (Priestley & Taylor, 1972) to estimate potential evapotranspiration. The Priestley-Taylor equation requires inputs of air temperature, dew point, date, and time – an advantage over other methods that require more complex inputs such as wind and aerodynamic roughness, which can be unreliable and difficult to estimate, and in fact are rarely measured at river gauging stations.

3.3.1.2 Canopy interception

The consideration of canopy interception in TopNet is based upon the work of Ibbitt (1971). Two parameters are required to estimate canopy interception: canopy interception capacity and an interception evaporation adjustment factor. This method of estimating canopy interception is advantageous when dealing with limited input data, which can be common in New Zealand catchments.

3.3.1.3 Soil

The soil component for TopNet considers the soil matrix to a depth that is influenced by tree roots and their ability to extract water from the soil. It is influenced by precipitation throughfall and evapotranspiration, which are estimated from the canopy interception component of the model. The TopNet soil component considers both saturation excess runoff generation and infiltration excess runoff generation, whereas the previous Topmodel soil component considered only saturation excess, and assumed an effectively unlimited infiltration capacity that did not allow for infiltration excess runoff. TopNet employs both gravity drainage and Green-Ampt concepts to allow surface runoff generation by infiltration excess overland flow, yet also considers drainage to saturated zones and the effects of evapotranspiration.

3.3.1.4 Saturated zone

The saturated zone component of TopNet is built upon the Topmodel assumptions of “saturated hydraulic conductivity decreasing exponentially with depth [from the surface], and saturated lateral flow driven by topographic gradients at steady state” (Bandaragoda, et al., 2001, p. 182). From these assumptions, estimates of local and average depth to the water table can be made, allowing groundwater recharge and subsurface flow to be described. High resolution in the saturated zone was considered a low priority when TopNet was developed, so the model was programmed to assign one state variable to each subcatchment, instead of a state variable for each geospatial unit and wetness state, as is the case in Topmodel. As a result, the TopNet component for the saturated soil zone is less complicated than the Topmodel component and more computationally efficient.

3.3.1.5 Channel routing

The inclusion of a channel routing process in TopNet is a key advancement from Topmodel that allows TopNet to be applied to larger systems of catchments and subcatchments. In the TopNet model, the three sources of runoff from each subcatchment are: saturation excess runoff, infiltration excess runoff, and base flow. There is a delay between the generation of rainfall runoff and the runoff reaching the outlet due to the time taken for runoff to flow overland or in the saturated zone and reach and then travel through the stream network. A kinematic wave routing algorithm is used to model the flow through the stream network.

Inputs of Manning's channel roughness coefficient n, channel width, slope, and length for each segment of the network are required.

3.3.2 Basin Processes in the TopNet Model

The physical processes modelled by TopNet in each subcatchment pertain to the storage of water before it reaches the stream network. The five primary storage components are: canopy storage S_c, soil storage in the root zone S_r, aquifer storage S_a, overland or surface storage S_o, and snowpack storage S_s. They are modelled by a system of five differential equations. However, TopNet does not solve the equations simultaneously, rather in the order S_c, S_s, S_r, S_a, S_o, for each timestep. This reduces computational expense, as does employing analytical solutions where applicable.

3.3.2.1 Canopy Storage (S_c)

The canopy storage model was based on the work of Ibbitt (1971), such that

$$\frac{dS_c}{dt} = p - p_t - e_c \tag{3.1}$$

where p is the rate of precipitation, p_t is the rate of throughfall of the canopy, and e_c is the rate of evaporation from the canopy.

p_t and e_c are functions of S_c, such that

$$p_t = pf(S_c) \tag{3.2}$$

and

$$e_c = e_{pot}c_r f(S_c) \tag{3.3}$$

where c_r denotes a parameter used to quantify evaporation losses from interception relative to the potential evapotranspiration rate e_{pot}, determined using the Priestly-Taylor method, and where

$$f(S_c) = \frac{S_c}{C_c}\left(2 - \frac{S_c}{C_c}\right) \tag{3.4}$$

and C_c is the water holding capacity of the canopy.

The physical implication of these equations is that as the canopy nears its water-holding capacity, the rate of increase of canopy storage decreases, resulting in increased throughfall.

3.3.2.2 Soil Storage (S_r)

Soil and subsurface storage is arguably the most complex physical process modelled by TopNet. The adoption of the topographic index $a/\tan\beta$, developed by Beven and Kirkby (1979) for Topmodel, allows subcatchment variability to be quantified. a denotes the upslope area per unit contour width draining through a point, and $\tan\beta$ is the slope at that point. Points with a similar topographic index, resulting from the relationship between upslope area and local slope, are considered to have a similar hydrologic state and consequently display a similar response to change. An area containing points with a higher topographic index is more likely to become saturated more rapidly and may contribute more significantly to surface or subsurface storage.

The depth to the water table at a point z can be computed from the topographic index

$$z = \bar{z} + m[\lambda - \ln(a/\tan\beta)] \qquad 3.5$$

or

$$z = m - (m - \bar{z})\frac{(a/\tan\beta)^{1/n}}{\lambda_n} \qquad 3.6$$

where $\bar{z}$ is the spatial average of the depth to the groundwater table, m is a depth scaling parameter, n is a dimensionless parameter, and λ and λ_n are the spatial averages of the transformed topographic indices $\ln(a/\tan\beta)$ and $(a/\tan\beta)^{1/n}$, respectively such that

$$\lambda = \frac{1}{A}\int_A \ln(a/\tan\beta) \qquad 3.7$$

and

$$\lambda_n = \frac{1}{A}\int_A (a/\tan\beta)^{1/n} \qquad 3.8$$

and A is the basin area.

The local depth to the water table in relation to the depth of the soil layer and the ground surface is used to determine whether the catchment soil layer is *saturated*, *influenced*, or *uninfluenced* by the local groundwater. If the depth to the water table z lies below the soil layer, the soil layer is uninfluenced, if z lies within the soil layer, the soil layer is influenced by groundwater, and if z is located above the soil layer, denoted by a negative value of z, the soil layer is saturated by the water table.

Once the fractional areas of each zone ϕ_{unf}, ϕ_{inf}, and ϕ_{sat} have been determined, along with a cumulative distribution function of the transformed topographic index κ, the storage and the rate of change of storage for each zone can be computed, allowing the change in storage to be determined

$$\frac{dS_r}{dt} = \frac{dS_{unf}}{dt} + \frac{dS_{inf}}{dt} + \frac{dS_{sat}}{dt} \quad 3.9$$

where *unf*, *inf*, and *sat* denote uninfluenced, influenced, and saturated zone, respectively.

It should be noted that the restriction is imposed that the relative change in soil moisture is constant across the zones

$$\frac{dS_r}{dt} = \frac{1}{\phi_{unf}}\frac{dS_{unf}}{dt} = \frac{1}{\phi_{inf}}\frac{dS_{inf}}{dt} = \frac{1}{\phi_{sat}}\frac{dS_{sat}}{dt} \quad 3.10$$

This condition may pose some restrictions on processes such as infiltration, soil evaporation, and drainage but results in a more efficient model.

3.3.2.3 Aquifer Storage (S_a)

Under ideal conditions, the groundwater state equation to describe aquifer storage S_a is

$$\frac{dS_a}{dt} = d - q_b \quad 3.11$$

where d is the drainage rate and q_b is the rate of baseflow, or aquifer discharge rate.

Change in aquifer storage can be defined as a function of the change in the average water table depth $d\bar{z}$ and the drainable water content across the basin θ_1. Hence, the groundwater state equation can be rewritten as

$$-\theta_1 \frac{d\bar{z}}{dt} = d - q_b \quad 3.12$$

The overall drainage rate d is the summation of the drainage from each soil zone, such that

$$d = \phi_{unf} d_{unf} + \phi_{inf} d_{inf} + \phi_{sat} d_{sat} \quad 3.13$$

And baseflow rate q_b is a function of hydraulic conductivity, topographic index, and average water table depth.

3.3.2.4 Surface Storage (S_o)

Surface runoff can be generated as infiltration-excess runoff q_{ix}, as saturation-excess runoff q_{sx}, and as baseflow discharge q_b. Hence the state equation for surface storage S_o is a simple mass-balance equation

$$\frac{dS_o}{dt} = q_{ix} + q_{sx} + q_b - q_o \tag{3.14}$$

where q_o is the runoff flow from the surface storage component to the river network, where it is no longer considered surface storage but rather part of the streamflow.

Because the movement of runoff from the land surface to the river network is not instantaneous, at any point in time there will be water storage on the surface before it enters the river network. TopNet assumes that the three forms of runoff do not enter the river network immediately, and instead must spend time as surface storage. When considering baseflow discharge, this implies that groundwater is discharged into small streams that are not considered by the modelled river network.

Infiltration-excess runoff is generated when the rate of precipitation exceeds the rate of infiltration. It occurs in both the influenced soil zone and the uninfluenced soil zone, but to differing degrees, hence the fractional area of each zone ϕ_{unf} and ϕ_{inf} must be considered. Saturation-excess runoff is generated only in the saturated zone of a catchment and when runoff forcing is positive. Infiltration is taken to be zero and saturation-excess runoff is determined by considering the rate of precipitation and fractional area of the saturated zone.

Basin outflow or discharge from surface storage q_o requires the consideration of a time delay to account for the transportation of overland flow. The delay is determined using the frequency distribution of overland flow residence time τ, derived from the empirical frequency distribution of overland path length x and overland flow velocity v.

3.3.2.5 Snowpack Storage (S_s)

Put simply, the rate of change of snow water equivalent storage is

$$\frac{dS_s}{dt} = p_s - m_s \tag{3.15}$$

where p_s is the rate of throughfall of snow through the canopy and m_s is the rate of snowmelt.

The rate of snowmelt can be determined through ambient temperature and, if available, solar radiation, wind, precipitation, and other climate inputs.

3.3.3 River Network Processes

The river network processes considered in TopNet are flow routing within the river network and storage of water in lakes and reservoirs. The consideration of these processes in TopNet is critical in enabling the model to be applied to larger catchments and catchment networks.

3.3.3.1 Rivers

Flow routing or channel routing in TopNet is modelled by a one-dimensional Lagrangian kinematic wave routing scheme. Runoff generated in each sub-basin is disseminated as discrete particles through the stream network to the catchment outlet.

When determining discharge per unit channel width q it is assumed that the channel is hydraulically wide so that water depth h is a good approximation for the area of the channel. Manning's stage-discharge relationship gives

$$q = \frac{\sqrt{s}}{n} h^{5/3} \tag{3.16}$$

where s is the channel slope and n is Manning's resistance coefficient with units of s/m^3.

Furthermore, the celerity of the runoff particle v is

$$v = \alpha \left(\frac{\sqrt{S}}{n}\right)^{3/5} q^{2/5} = \frac{dq}{dy} \tag{3.17}$$

where α is the Priestly-Taylor runoff coefficient. The time taken for an individual flow particle to travel along a length of channel segment τ is given by

$$\tau = \frac{L}{v} \tag{3.18}$$

where L is the length of channel segment. This is comparable to the computation of overland flow residence time under basin processes.

Water resource management strategies such as irrigation, dams and reservoirs, and water abstraction are also able to be modelled in TopNet, however they are not pertinent to the Ahuriri River catchment model and the Pelorus River catchment model, and so fall outside the scope of this research.

3.4 Model Inputs

TopNet is a rainfall-runoff model; hence the most important input to the model is precipitation. However, other inputs to TopNet can include:

- Maximum, minimum, instantaneous, and average temperature;
- Relative humidity;
- Dewpoint temperature;
- Shortwave and longwave radiation;
- Wind speed; and
- Mean sea level atmospheric pressure.

Most TopNet models for New Zealand catchments have been developed to make predictions with minimal inputs. Many catchments in New Zealand are ungauged, so no flow or climate data exist to input to the model or for model calibration and validation. As such, the model may require only precipitation, maximum temperature, and minimum temperature inputs, although the models can be modified to take advantage of more climate data where available. The precipitation inputs are taken from NIWA's Virtual Climate Station Network (VCSN) at a daily timestep, and the temperature inputs are taken from the nearest neighbouring actual climate station. In addition to the VCSN and nearby climate stations, model inputs can be taken from: an inverse distribution of climate variables, such as precipitation and temperature, based on observed data; inverse distribution and mean surface values of climate data; inverse distribution coupled with the VCSN; or simply estimated.

The VCSN is a New Zealand-wide 5 km grid that provides estimates for climatic variables, such as rainfall and temperature, and is necessitated by the need for climate data across the country coupled with constraints in funding and access that prevent a comparable network of actual climate stations. The VCSN employs a spline interpolation scheme and mesoscaling factors to scale rainfall and other climate variables (Andrew & Richard, 2005). While the VCSN is the product of a relatively advanced method of estimating climate parameters, a method that is generally agreed to be appropriate, it is still subject to error. Error in rainfall interpolation can generally be attributed to insufficient actual data on which to base the VCSN estimates, and this is particularly true for the VCSN in alpine regions of elevation greater than 500 m ASL. The majority of gauging stations that supply data to the VCSN are located below 500 m ASL. This has resulted in a low-density network of stations at high altitude, and so interpolated values for precipitation in the VCSN in alpine regions are likely to have higher error – in fact, some interpolations in the VCSN may be based on storms that occurred outside a particular catchment, or some storms may be missed entirely by the sparse network of stations and so not included in the VCSN at all (Tait, Sturman, & Clark, 2012).

When using data from the VCSN in regions with elevation less than 500 m ASL, error on *rain days*, where the VCSN predicts daily rainfall greater than zero, can be expected to fall between 2 mm and 4 mm. On *heavy rain days,* where VCSN predicts daily rainfall greater than 40 mm, the error in daily rainfall can be expected to be between 8mm and 12 mm. For areas of elevation greater than 500 m ASL, the error in the VCSN data can be expected to be between 5 mm and 15 mm on rain days and between 10 mm and 40 mm on heavy rain days. Hence, it can be expected that the VCSN will produce greater error for larger rainfall events, especially in alpine regions (Tait et al., 2012).

Error in rainfall input to a hydrologic model, be it error in rainfall volume, spatial distribution, or temporal distribution, can result in significant error in the model predictions. While the error in the VCSN has been studied, it is still difficult to quantify for specific events and locations. An important product of significant error in the rainfall input to a rainfall-runoff model may be a reduced ability to identify other sources of error. For example, rainfall error can hide errors from improper parameter selection and model calibration (McMillan, Jackson, Clark, Kavetski, & Woods, 2011).

Daily rainfall from the VCSN at each grid point within the catchment is disaggregated into hourly rainfall by the TopNet model to allow hourly rainfall runoff and streamflow to be predicted. The disaggregation of daily rainfall can be stochastic or can be based on observed rainfall at the nearest actual climate station data (Figure 3-12). While both provide the same total daily rainfall input to the model, the rainfall distribution based on actual rainfall data is likely to be a more accurate representation of temporal rainfall distribution, especially if the nearest station is in close proximity to, or within the catchment being modelled.

Four precipitation gauging stations are located within the Ahuriri River catchment. Two of the stations are located toward the top of the catchment, and two near the outflow of the Ahuriri River (Figure 3-13). The stations have been managed by NIWA, ECan, and Meridian Energy. The oldest station provided a data series from 1970, while the newest provided a data series from 1992. The observations from all four stations contained periods where, for reasons that may include maintenance downtime, instrumental error, or disestablishment of the station, no data exist. Only one station in the upper reaches of the catchment and one downstream appeared to have been operational at any point in time since 1970. Hence, all estimates of precipitation distribution for the Ahuriri River catchment were based on two sets of precipitation data; one from the upper reaches and one from the lower reaches of the catchment.

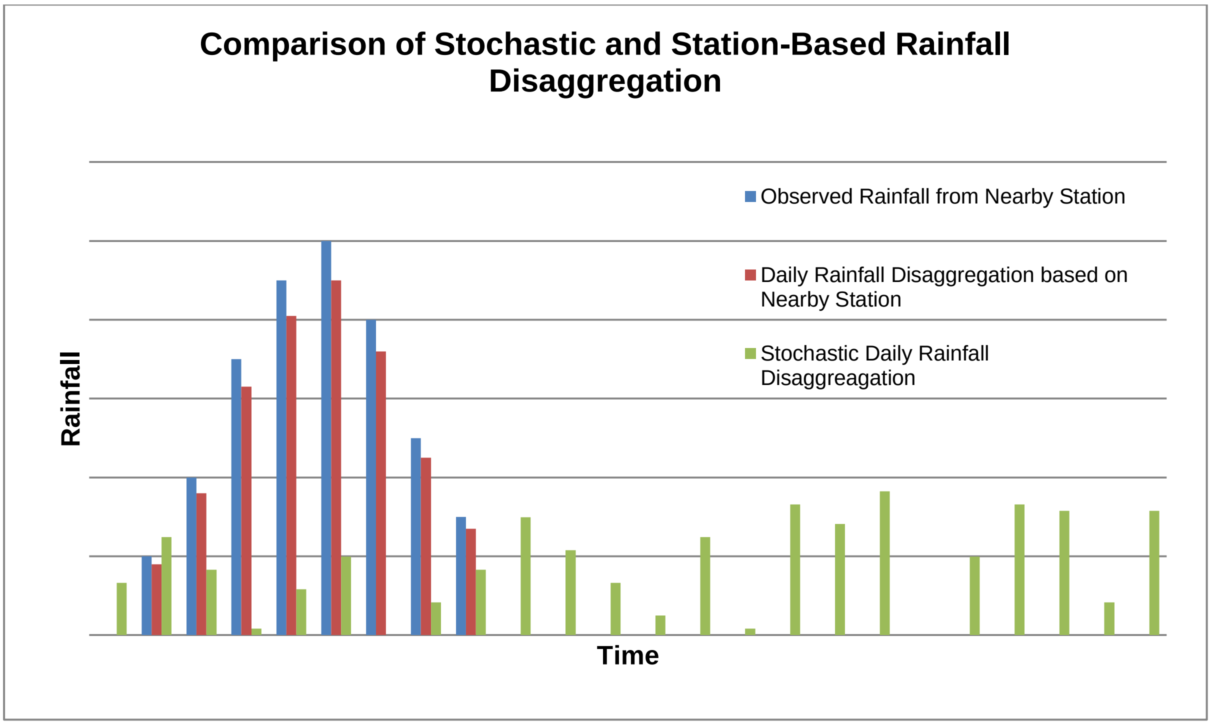


Figure 3-12: Representation of the potential difference between stochastic and station-based rainfall disaggregation

Note: Figure 3-12 is not based on an actual rainfall event; it is for demonstrative purposes only.

The Pelorus River, on the other hand, did not have any rain gauges within its watershed. TDC and MDC operate five gauging stations that can be applied to the Pelorus catchment, all located within 8 km of the catchment boundary (Figure 3-13). However, the gauges were primarily for flood warning and both Councils have acknowledged that the quality of data was likely to be poor due to the low priority of the gauges and the low level of funding the gauges receive. Since 1970, two or three of the five gauges have been operational at any time; hence any precipitation observations were based on between two and three sets of rainfall data. In addition to being located outside the Pelorus River catchment, the stations were concentrated around the lower, northeast half of the catchment. Hence, data collected by the stations may not have accurately represented the rainfall distribution in the Pelorus River catchment.

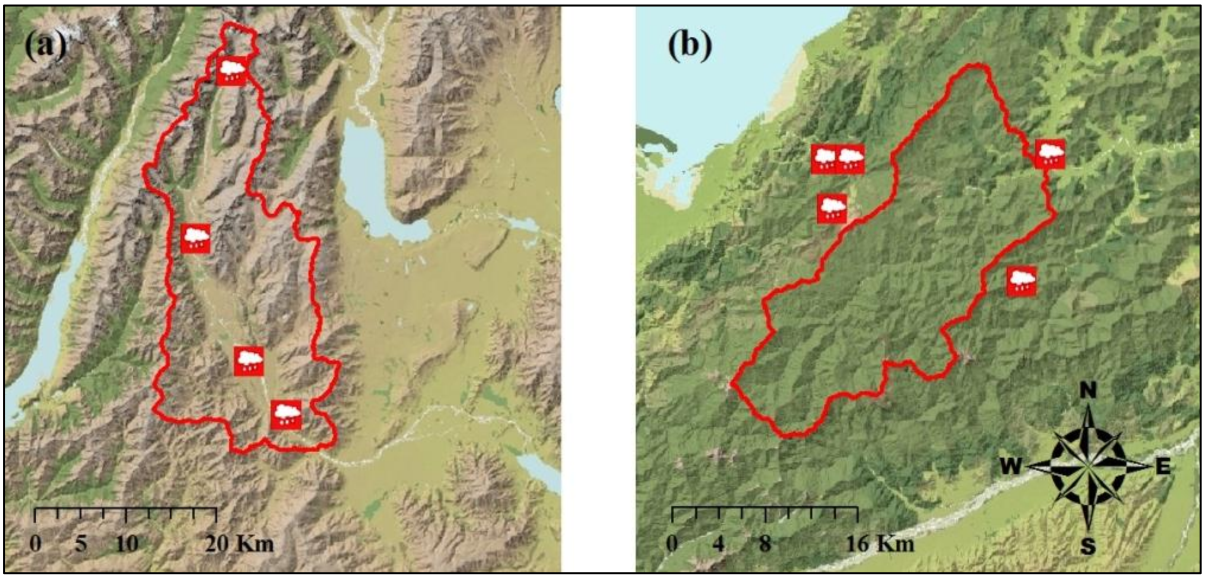


Figure 3-13: Location of rainfall gauging stations in the (a) Ahuriri and (b) Pelorus River catchments

The model predicts soil moisture content and groundwater level based on climate data input from the VCSN, such as precipitation, temperature, wind, and seasonal effects, depending on the intended use of the model and the availability of data. For the TopNet models developed for the Ahuriri and Pelorus River catchments, the inputs were temperature and precipitation. The initial environmental conditions in the model were estimated and were unlikely to be an accurate representation of the actual environmental conditions in the catchment. To account for this, the models were run for a 'spin-up' period of at least 100 days prior to the desired flow period to ensure the antecedent catchment conditions reflected the climate conditions in the catchments as closely as possible, and hence derive more accurate flow predictions.

3.5 Testing the TopNet Model for Flood Flow Predictions

TopNet has been primarily used to model continuous water yield across a catchment. While the calibration and validation of the models for the Ahuriri River catchment and the Pelorus River catchment gave some regard to flood peaks, they were not specifically developed or calibrated for modelling such phenomena. Hence, a detailed investigation was performed to assess whether TopNet may be a useful modelling tool for predicting high flow events in mountainous catchments in New Zealand using the models developed for the Ahuriri and Pelorus River catchments.

3.5.1 Calibration of the TopNet Models

Calibrating a hydrologic model is the process of adjusting the estimated model parameters until the model flow prediction and the measured flow data agree to an acceptable level. This can be done qualitatively, by visual inspection of predicted and observed hydrographs or other outputs after adjusting the model parameters, or by quantifying error in the model simulations using objective functions. NIWA developed and calibrated the TopNet models for the two catchments; therefore the scope of this investigation did not include calibrating the models. However it was important to know the mechanisms by which TopNet models are calibrated.

The model parameters in TopNet represent the physical characteristics of the catchment and are generally assumed not to be subject to temporal variation. These include soil properties, topography, land cover, and channel properties. In the application of TopNet in the DMIP the parameters were estimated from GIS datasets and applied to the catchment (Bandaragoda et al., 2004). They were either uniform across the catchment, spatially variable and calibrated, or left uncalibrated. While there were 18 parameters in the TopNet model, only five parameters were considered important to the calibration of the model. They were: saturated store sensitivity; surface saturated hydraulic conductivity; overland flow velocity; canopy intercepted evaporation enhancement; and Manning's *n*. The remaining 13 parameters were discounted for a number of reasons, including their negligible influence on the model prediction, spatial uniformity across the catchment, and confidence that the parameters were correct prior to the model calibration. Calibrating the model using five parameters significantly reduced computational time and allowed sources of error to be more easily identified. Computational expense of the model calibration was also minimised by applying a multiplier to each parameter across the catchment instead of modifying the parameters in each subcatchment individually. This reduced the degrees of freedom of the model, and also maintained the spatial variation in physical properties of each sub-basin. This calibration process was adopted by Guzha and Hardy (2010) to develop a TopNet model for the Big Darby Creek Watershed, Ohio, and is typical of a TopNet model calibration.

The Ahuriri and Pelorus River catchment models were calibrated over a 3-year period (1998 – 2001). The calibration period was selected so that each of the years in this period were characterised by one higher-than-average annual precipitation, one lower-than-average annual precipitation, and one approximately average annual precipitation. The models were calibrated against VCSN rainfall estimates, using stochastic disaggregation of daily rainfall to hourly rainfall. In effect, the catchments were treated as though no actual climate data were available – a characteristic of many New Zealand catchments. While some attention was given to the accuracy of predicting flood peaks during the model calibration period, more focus was given to water yield and the cumulative discharge of the catchments. The models were each validated over much of the duration of flow data available; the Ahuriri River catchment model was validated over the period 1972 – 2010, and the Pelorus River catchment model was validated over the period 1977 – 2010.

3.5.2 Objective Functions

Put simply, an objective function is a means of quantifying the error in a model prediction. Calibrating a model is the process of identifying the values of the model parameters that optimise the objective function, and validation attempts to produce optimised objective functions without any further parameter modification. A variety of objective functions exists that are applicable to hydrologic modelling.

3.5.2.1 Nash-Sutcliffe Efficiency (NSE)

The NSE was developed by Nash and Sutcliffe (1970) and is analogous to the Pearson correlation coefficient R^2. It has been widely used to quantify error and efficiency of hydrologic models and is applicable continuous water balance models, sediment transport models, flood models, and others (McCuen, Knight, & Cutter, 2006). In fact, the NSE has often been used to quantify error in TopNet models (Bandaragoda, et al. 2004; McMillan and Clark, 2009; and others). The NSE, which is dimensionless, can be defined as

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(q_{m,i} - q_{o,i}\right)^2}{\sum_{i=1}^{n} \left(q_{o,i} - \mu_o\right)^2} \qquad 3.19$$

where n is the total number of iterations or timesteps of the model, $q_{m,i}$ is the modelled value at iteration i, $q_{o,i}$ is the observed value at the time of iteration i, and μ_o is the mean of the observed values.

The NSE generally ranges between 0 and 1, although the value may be less than zero. An acceptable NSE is largely subjective and depends on the purpose of the model; however in the calibration of a TopNet model for the DMIP, Bandaragoda et al. (2004) judged an efficiency of 0.7 or greater to be acceptable and sufficiently explain the variance in the model.

While it is a common measure of model efficiency, the NSE does have shortfalls. It has been found that a relatively poor hydrologic model may give a NSE value close to one, which may lead to false confidence in the model. This can occur when the statistical variance of the observed or modelled flow is high (Jain & Sudheer, 2008).

McCuen et al. (2006) conducted a study to present an approximate sampling distribution of the NSE, and assess factors that may influence the computed NSE. The study found that outliers can have a significant influence on the computation of the NSE, analogous to the effect of large variance in the flow data. The influence of model bias was also explored, and found to have a significant effect on NSE. Bias $\bar{e}$ and relative bias R_b is computed as

$$\bar{e} = \frac{1}{n}\sum_{i=1}^{n}\left(q_{i,m} - q_{i,o}\right) \text{ and } R_b = \frac{\bar{e}}{\overline{q_o}} \quad 3.20$$

Larger bias and relative bias in the model may have a greater influence on the value of NSE, to the extent that a relative bias of 40% was found to reduce the sample NSE to zero. Bias in the model may be considered significant if the relative bias is greater than ±5%. Generally, a negative bias indicates that the model will underpredict flow, and a positive bias indicates that the model will overpredict flow (McCuen et al., 2006).

The study also explored the influence of time-step size and, by association, sample size, given that a smaller time-step will necessitate more iterations, thus increasing the sample size. It was found that the length of time-step and the sample size did not have a significant effect on the computed NSE, provided the time-step maintained a moderate length. As statistical theory would indicate, increasing the time-step significantly, and thus reducing the sample size, caused the error in the model to increase significantly also. This suggested that, for the most part, NSE was not sensitive to time-step or sample size, allowing it to be applied to event modelling over relatively short timescales. However, consideration must be given to outliers and data variance, model bias, and other influences when considering the implications of the computed NSE (McCuen et al., 2006).

3.5.2.2 Root Mean Squared Error (RMSE)

The RMSE is another common objective function used to quantify the efficiency and error of a model. It can be computed as

$$RMSE = \left(\frac{1}{n}\sum_{i=1}^{n}\left(q_{m,i} - q_{o,i}\right)^2\right)^{1/2} \quad 3.21$$

When comparing Eq. 3.21 to Eq. 3.19 it is clear that the RMSE and the NSE are related. However, while the NSE is non-dimensional, the RMSE has units dependent on the criterion variable. Furthermore, the NSE is subject to maximisation as it approaches 1, indicating zero model error, while the RMSE is subject to minimisation as the error approaches zero. The similarities between the RMSE and the NSE extend to the limitations of the objective functions, and as such any consideration given to the NSE should also be given to the RMSE (Gupta, Kling, Yilmaz, & Martinez, 2009).

The peak-weighted root mean square error (PWRMSE) is similar to the RMSE, with the inclusion of a weighting factor to give more influence to error near the peak discharge. When RMSE and PWRMSE were compared in the calibration of an event model, it was found that the error improved when weighted by peak (Cunderlink & Simonovic, 2004). PWRMSE can be computed as

$$PWRMSE = \left(\frac{1}{n}\sum_{i=1}^{n}\left(q_{m,i} - q_{o,i}\right)^2 \frac{q_{o,i} + \mu_o}{2\mu_o}\right)^{1/2} \quad 3.22$$

3.5.2.3 Least Squares Function (F)

The least squares function F is a commonly used objective function in hydrologic modelling (Asaad, 2005). It is the sum of the squared differences between the predicted flow values and observed flow values. It can be computed as

$$F = \sum_{i=1}^{n}\left(q_{m,i} - q_{o,i}\right)^2 \quad 3.23$$

When comparing Eq. 3.23 to Eq. 3.21, F is analogous to RMSE, with the addition of the $1/n$ term to determine RMSE. Hence, F is subject to minimisation as the error approaches zero, and is also subject to similar shortcomings.

3.5.2.4 Time to Peak Error (TPE)

TPE measures temporal error between the observed hydrograph peak and the predicted peak (Mediero, Garrote, & Martín-Carrasco, 2011). TPE is measured in units of time, and optimised at zero, indicating there is no difference between the occurrence of the predicted peak flow and the observed peak flow. It can be calculated as

$$TPE = i\left(q_{o,peak}\right) - i\left(q_{m,peak}\right) \quad 3.24$$

where $i(q_{o,peak})$ and $i(q_{m,peak})$ are the instantaneous time at which the observed peak flow and modelled peak flow occur, respectively. The TopNet models predicted runoff at an hourly timestep so the TPE for the TopNet model predictions were measured in hours.

3.5.2.5 Per Cent Error in Peak Flow (PEPF)

The per cent error in peak flow (PEPF) is simply a measure of the error in peak flow prediction as a fraction of the observed flow. It can be computed as

$$PEPF = \frac{q_{m,peak} - q_{o,peak}}{q_{o,peak}} \times 100\% \qquad 3.25$$

PEPF is optimised as it reaches 0%, indicating that observed and modelled flows are equal. It has no upper limit. PEPF also indicates whether the model is over-predicting or under-predicting peak flow, based on the positivity or negativity of the function solution (Caruso et al., 2013).

3.5.3 Selection of Events to Evaluate the TopNet Models

There appears to be no established criteria for selecting flow data for hydrologic model calibration, validation, or testing. For a continuous hydrologic model, the selection is based on flow duration and location in time. Liu and Han (2010) ponder two questions: “how long should the calibration data be (e.g., 6 months), and from which period should the data be selected (e.g., which 6 month data should be selected)”. For an event-based model, variables such as flow peak, depth of precipitation, and storm duration can be considered (Lamb, 1999). Historical flow records can be used to calibrate and validate the model to a variety of return-period flow events. Differences in storm meteorology can also be used, such as calibration to a frontal storm and a convective storm (Cunderlink & Simonovic, 2004), however this can be complicated.

Given the lack of established criteria for selecting calibration and validation events, the selection of events to test the TopNet models was somewhat subjective. For this research project, three events were selected to test the use of the TopNet models that had been developed for each catchment. Selection of events was based on:

- Average return interval of the flood (ARI), to ensure a selection of flow magnitudes and frequencies were considered;
- The availability of observed flow data to compare the model predictions to the observed flow; and
- The availability of observed precipitation data for the time period to be modelled so that station-based rainfall disaggregation may be applied to the model.

The events used to test the models for the Ahuriri and Pelorus River catchments are presented in Table 3-2 and Table 3-3, respectively.

Table 3-2: High flow events to be used in the model testing for the Ahuriri River catchment

Date of Event	Peak Flow	ARI (Caruso et al., 2013)	Comments
9 Jan 1994	568 m^3/s	43 years	Largest event on record
16 Nov 1999	371 m^3/s	7.5 years	Complex observed hydrograph displaying double-peak
19 Sep 2002	291 m^3/s	3.7 years	Complex observed hydrograph displaying step-wise rising limb

As part of a wider flood-modelling exercise in the Ahuriri River catchment, Caruso et al. (2013) analysed flow data to determine the statistical distribution that best modelled flood flows on Ahuriri River. The study found that floods in the catchment are best modelled by the 3-parameter Lognormal distribution or the Generalised Extreme Value (GEV) distribution, and it was suggested that an average of the two distributions would give sensible probabilities for events with AEP less than 0.01 or ARI less than 100 years. Hence, such an approach has been taken for this project when considering flood flows in the Ahuriri River catchment. The average of the GEV and Lognormal distributions was used to determine the ARI for each historical event that occurred on the Ahuriri River.

Table 3-3: High flow events to be used in the model evaluation for Pelorus River catchment

Date of Event	Peak Flow	ARI	Comments
1 July 1998	1678 m^3/s	21 years	Second-largest event on record, complex hydrograph
23 Feb 1995	1622 m^3/s	18 years	Third-largest event on record
30 Jan 2000	1389 m^3/s	9.3 years	Short duration for flood event

While the flood flows in the Pelorus River catchment have not been extensively analysed, a distribution was selected and applied to the flow records to develop an ARI curve to be used in this investigation. Studies have suggested that distributions in the extreme value family best represent flood flows in New Zealand catchments (Pearson & Henderson, 2004). Positive results using the GEV distribution in the steep Ahuriri River catchment (Caruso et al., 2013) and the mountainous Mulde catchment in Germany (Petrow, Merz, Lindenschmidt, & Thieken, 2007) suggested that the GEV distribution is well-suited to steep catchments. Hence, the GEV distribution was applied to the Pelorus River annual maxima series of flood peaks to determine the return period of evaluation events and high flow events. The GEV distribution for the river is presented in Figure 3-10. The Kolmogorov Smirnoff and Chi-Squared goodness of fit values for the GEV distribution were 0.09 and 0.61, respectively, indicating that the distribution is a good model of flood frequency for the Pelorus River from the observed data record. The 3-parameter Lognormal distribution and 3-parameter Weibull distribution have comparably high goodness-of-fit indicators, but the GEV distribution was chosen based on historical application to New Zealand rivers.

In addition to evaluating the model performance using three historical events, the models were run over the original calibration period to evaluate the model calibration. For both the Ahuriri River and Pelorus River catchment models the calibration period was from 1998 to 2001. This period of three years was considerably longer than the duration of the flood modelling periods used for this project, which considered flow over a duration of less than a week. A number of high flow events occurred during the calibration period, although the models were not calibrated specifically to predict these events. Hence, evaluation of the calibration period may provide a useful assessment of the ability of TopNet to model water balance over an extended period, which is a primary use of the model in its current form.

3.5.4 Testing the Models

Once the existing models were run and runoff hydrographs generated for the selected high flow events, the observed and predicted storm hydrographs were compared and the error between the hydrographs quantified to allow conclusions to be drawn regarding the ability of the models to predict flood flows for the current land use in each catchment. The models were run using stochastically disaggregated daily rainfall as a model input and daily rainfall disaggregation based on station data as inputs. This was intended to allow quantification of the effect each method of rainfall disaggregation had on the accuracy of the models.

Key outputs considered in the model evaluation were the values of objective functions applied to the observed and predicted hydrographs and a visual comparison of the model output and observed hydrographs, which identified any obvious error.

While a number of objective functions have been discussed, many of them employ similar mechanisms and can be expected to give similar measures of error. Hence the NSE was the primary objective function used to evaluate model performance. PEPF and TPE were also employed as these simple objective functions focus on important parameters in flood modelling of peak flow magnitude and the timing of the flood peak. The value of the objective function that constitutes a ‘good’ or ‘acceptable’ model prediction was subjective, although it had been suggested that a NSE of 0.7 was acceptable and able to explain the error in a model (Bandaragoda et al., 2004). The relative bias R_b of each model prediction was also calculated since model bias can influence the efficiency of a hydrologic model.

The objective functions focussed on how accurately the models predicted peak flows, but it was important to identify which section of the hydrograph before and after the peak to include in the evaluation. Selection of the period over which the objective functions were applied was subjective and determined on a case-by-case basis, ensuring that each evaluation period was long enough to include the rising limb of the hydrograph, the flood peak, and a reasonable section of the falling limb of the hydrograph. In most cases, this occurred over a period of between 72 and 120 hours (3 to 5 days), and appeared to be dependent on the flood magnitude and the duration of the storm.

To assist in the evaluation of the model, and in an attempt to identify rainfall input as a potential source of error in the model predictions, the observed rainfall hyetographs and the rainfall hyetographs input to the models by the VCSN were compared. Attention was given to the total rainfall across the catchment and the distribution of the rainfall. The Ahuriri River catchment had a consistent rainfall record from four gauging sites within the catchment boundaries, and two of the stations were operational at any time. Hence, it was expected that comparing the observed rainfall hyetograph with the rainfall provided by the VCSN in the Ahuriri River catchment would allow the error in rainfall input to be quantified. The rainfall for each event was taken as an average of the observed rainfall at the active precipitation gauge sites within the Ahuriri River catchment that recorded the event (Figure 3-13). The Pelorus River catchment, however, did not have a rain gauge station within its boundary; rather the rainfall data was provided from two or three stations out of a total of five stations, depending on the timing of the event, located near the downstream end of the catchment (Figure 3-13). A comparison between the VCSN rainfall estimate and the observed rainfall data for each event used in the evaluation of the model was still conducted for the Pelorus River catchment. However, the observed data may not have been an accurate reflection of the actual precipitation event that lead to the high flow event in the Pelorus River.

The models were also run over the period used by NIWA in the calibration of each model. The models were calibrated to a stochastic disaggregation of the daily rainfall estimate. In effect, by using the daily rainfall estimate disaggregated into hourly rainfall using observed station data as a model input, as well as running the model using stochastic disaggregation of daily rainfall as an input, the model simulated a different rainfall series, albeit with the same net rainfall over the period. It was intended that this would assess the calibration of the model, attempt to quantify the difference between the two rainfall input methods, and provide some insight in to the accuracy with which the calibrated model parameters represented the physical processes in the catchment.

The evaluation of the models also determined which method of rainfall disaggregation to pursue for the remainder of the research project. While the models were calibrated using stochastic disaggregation of daily rainfall, station-based disaggregation may yield an improved rainfall input to the model and a greater level of accuracy in the model predictions, depending on the quality of the observed station data.

3.6 Modelling High Flow Events

An important question regarding the modelling of high flow events is: should a series of past events be modelled, or should a series of synthetic storm events be modelled, where rainfall input to the model is based on statistical estimates of intensity, return period, and duration? Since both methods were suitable for use in this investigation, the decision became somewhat subjective. If a selection of past events were to be run, events would be chosen based on the ARI of the peak flow such that a wide range of specific return period events were modelled with the ARI based on the GEV distributions for the Ahuriri River and the Pelorus River. The difference between the modelled flows and the observed data would be quantified in order to develop a relationship between the two data sets that may be carried forward in the project.

The selection of synthetic storm events may prove more complicated. The HIRDS database (NIWA, 2012a) can provide estimates for rainfall events with a selection of ARIs and storm durations. For each ARI, the database can estimate the precipitation for ten storm durations, ranging from the 10-minute storm to the 72-hour storm. Each storm of a particular duration will give a different peak flow and hence a different ARI for that flow, making it difficult to characterise the flood characteristics of each catchment. In fact, the prudent methodology for such an exercise would be to develop an ARI curve for each storm duration so that the flood characteristics of each catchment could be described concisely. Shortcomings of this method include a difficulty in comparing the modelled flood characteristics and ARI curves to the observed flood characteristics and ARI curve, since the observed characteristics and ARI curve had been developed independently of storm duration and based solely on observed flood peaks. Hence, confidence in the ARI curve developed using synthetic storm events would be based on the model evaluation, which occurred over three events as per the methodology of the project. Selecting one storm duration to model for a number of return period events has also been used (Woods et al., 2009). Most studies appear to come down to a matter of preference given both methods may be valid.

Hence, a series of past flood events was modelled. The series included a range of nine flood magnitudes that cover the range of ARIs from the GEV distribution applied to the observed flow records for each catchment (Table 3-4). This allowed the difference between the model flow predictions and the observed flow data to be quantified.

Table 3-4: Flood events to be modelled for each catchment

Ahuriri River catchment			Pelorus River catchment		
Date of event	Peak flow	ARI (Caruso et al., 2013)	Date of event	Peak flow	ARI
9 Jan 1994	*568 m^3/s*	*41 years*	21 Oct 1983	1735 m^3/s	24 years
21 Dec 1984	533 m^3/s	33 years	*1 July 1998*	*1678 m^3/s*	*21 years*
3 Dec 1979	514 m^3/s	28 years	*23 Feb 1995*	*1622 m^3/s*	*18 years*
13 Dec 1995	509 m^3/s	26 years	*30 Jan 2000*	*1389 m^3/s*	*9.3 years*
14 Oct 1978	377 m^3/s	7.9 years	23 July 1988	1234 m^3/s	6.0 years
16 Nov 1999	*371 m^3/s*	*7.4 years*	25 Jan 1986	1191 m^3/s	5.2 years
19 Sep 2002	*291 m^3/s*	*3.7 years*	13 June 1993	1140 m^3/s	4.5 years
28 Dec 2000	282 m^3/s	3.4 years	24 Jan 1991	964 m^3/s	2.7 years
30 Mar 1987	261 m^3/s	2.8 years	21 Apr 1987	958 m^3/s	2.6 years

Note: *Italicised events* indicate that the event was used for the evaluation of the model as well as in the modelling of flood events.

If the error was large in any of the simulated high flow events the potential sources of error were investigated. As discussed, error in the rainfall input was expected to be a significant source of error in the model predictions. A comparison of observed rainfall contributing to the high flow event and the rainfall input estimated by the VCSN and disaggregated into hourly rainfall by TopNet was conducted where required to determine whether rainfall input was a significant source of error. If the observed and estimated rainfall differed significantly, the corresponding event was discarded from the dataset under the grounds that the rainfall input was likely responsible for a large part of the error. From an engineering standpoint, the prediction of larger floods is considerably more important than the prediction of smaller flood events, since small flows are unlikely to pose risk to population or infrastructure. With this in mind, more importance was given to error in larger events. For flows with an ARI greater than 10 years, an error greater than 10% was required for further investigation into the rainfall for the event. However, for flows with ARI less than 10 years, an error greater than 40% was required to investigate rainfall since smaller flood flows are less important.

3.7 Modelling Future Land Use Scenarios

Several potential future land use scenarios were modelled to predict the effect of land use change on the flood hydrology of each catchment. The future land use scenarios modelled were:

- The reestablishment of native forest in the Ahuriri River catchment;
- The conversion of tussock and scrub to more widespread agriculture and pastoral activities in the Ahuriri River catchment;
- Forest harvesting and clearfelling in the Pelorus River catchment: and
- The conversion of forest to pasture in the Pelorus River catchment.

It is generally accepted that, prior to human activity in the UWB, the area had a significantly higher level of native forest cover (Caruso, 2006). Reforestation and reestablishment of native forest and scrub has become a somewhat attractive option for land use in New Zealand in the wake of the Kyoto Protocol. It has been suggested that native forest and scrub, such as manuka and kanuka, would be an effective carbon sink and could be profitable as a means of carbon trading (Trotter, Tate, Scott, & Townsend, 2005). A survey as part of a study near Gisborne found that landowners would consider a level of reforestation of 14% across the region to be appealing under the current carbons trading scheme, but this may increase as carbon trading has been forecast to become more appealing (Funk, 2009). Further benefits of native forest and scrub over grassland and pasture is increased stability of steep gullies resulting in decreased erosion (Marden, Arnold, Seymour, & Hambling, 2012). Hence, it is not unreasonable to expect that such a scenario may be considered in the Ahuriri River catchment or other catchments in the UWB.

Conversion of tussock grassland to agricultural land has been a feature of the UWB and much of the high country of New Zealand. Recent trends have pointed toward increased conversion to irrigated pasture for dairy farming. Irrigated pasture occupied 12,600 ha of the UWB as of 2009, and the appeal of dairy farming is high so this is likely to increase, despite concerns about the long term sustainability of the dairy industry (Addison, 2009). Furthermore, the conversion of land to pasture is a contentious issue in the UWB community; hence an attempt to quantify the effects of such land use change may prove useful. While the development of irrigated pasture may be a more contentious land use issue than low input pasture, primarily due to water resource management conflicts, the TopNet model developed for the Ahuriri River catchment did not include irrigation as an input. Hence, the conversion to low input pasture was modelled as a future scenario. This should give some indication of the effects of irrigated pasture since the hydrologic characteristics of the two land uses have been shown to be reasonably similar (Rowe et al., 2002).

Harvesting and clearfelling of exotic plantation forest can have a significant effect on the hydrology of a catchment. Commercial forestry is an important land use in the upper South Island, and while forestry operations are expected to develop a harvest management plan to mitigate effects on the catchment (NRC, 2012), it can be difficult to quantify the immediate effects of clearfelling before the forest can begin to re-establish itself. The land cover in the Pelorus River catchment is primarily native forest, but native forest has been shown to display similar hydrologic properties and have a similar influence on water balance and flood flows to plantation forestry (Fahey & Jackson, 1997).

Historically, the clearing of native forest to make way for pasture has been a significant feature of land use change in New Zealand. While less common now, in part due to the Kyoto Protocol and the attractiveness of carbon sequestration, and an increased sense of conservationism discouraging the clearing of native forest, the conversion of forested land to pasture still occurs. The effects of such conversion have been studied to some degree but there has been little focus on the effects on the hydrology and flood flows in steep catchments such as the Pelorus River catchment.

To model future land use scenarios in the Ahuriri and Pelorus River catchments, model parameters for the catchments were modified to reflect future land use scenarios. TopNet is a semi-distributed model, so larger catchments such as the Ahuriri and Pelorus River catchments are further delineated into smaller subcatchments of lower order streams. When they were developed, the models used in this research project were delineated to Strahler order 3 subcatchments, resulting in 61 subcatchments in the Ahuriri River catchment and 43 subcatchments in the Pelorus River catchment. As such, the parameters of each subcatchment were modified to reflect the spatial distribution of future land use scenarios, as it was unreasonable to expect land use change to occur across the whole extent of each catchment. The most important parameters when considering land use change in the TopNet model are saturated hydraulic conductivity, canopy water storage capacity, and the canopy evaporation enhancement factor (Woods et al., 2009). Hence, these were modified to reflect land use change in each catchment model.

Each subcatchment was evaluated to determine whether the intended land use change scenarios were reasonable using the Land Use Capability (LUC) map (Figure 3-14) from LRIS (2012) and the corresponding LUC class codes (Table 3-5) (Newsome, Wilde, & Willoughby, 2008). The map qualitatively describes the suitability of the land for forestry, pastoral, and agricultural activity. While there are a number of guiding documents on suitable land characteristics for different land uses (For example: Colley, 2005; ECan, 2009; NDC, 2012; TDC, 2008) in addition to the LUC map, determining subcatchments that may experience land use change was ultimately a subjective exercise. The extent of each scenario was varied to quantify the sensitivity of each mountainous catchment to land use change. While the LUC map identified small areas of either catchment to be suitable for future agricultural or forestry development, it was sensible to modify the land use across a larger area of each catchment to evaluate the sensitivity of rainfall runoff to land use change and so that the findings of the investigation may be applied to other, topographically-similar catchments that may be more suitable to extensive forestry or agricultural land use.

Table 3-5: Land Use Capability (LUC) class code and description (Newsome et al., 2008)

LUC Class Code	Description
1	Land with virtually no limitations for arable use and suitable for cultivated crops, pasture or forestry
2	Land with slight limitations for arable use and suitable for cultivated crops, pasture or forestry
3	Land with moderate limitations for arable use, but suitable for cultivated crops, pasture or forestry
4	Land with moderate limitations for arable use, but suitable for occasional cropping, pasture or forestry
5	High producing land unsuitable for arable use, but only slight limitations for pastoral or forestry use
6	Non-arable land with moderate limitations for use under perennial vegetation such as pasture or forest
7	Non-arable land with severe limitations to use under perennial vegetation such as pasture or forest
8	Land with very severe to extreme limitations or hazards that make it unsuitable for cropping, pasture or forestry

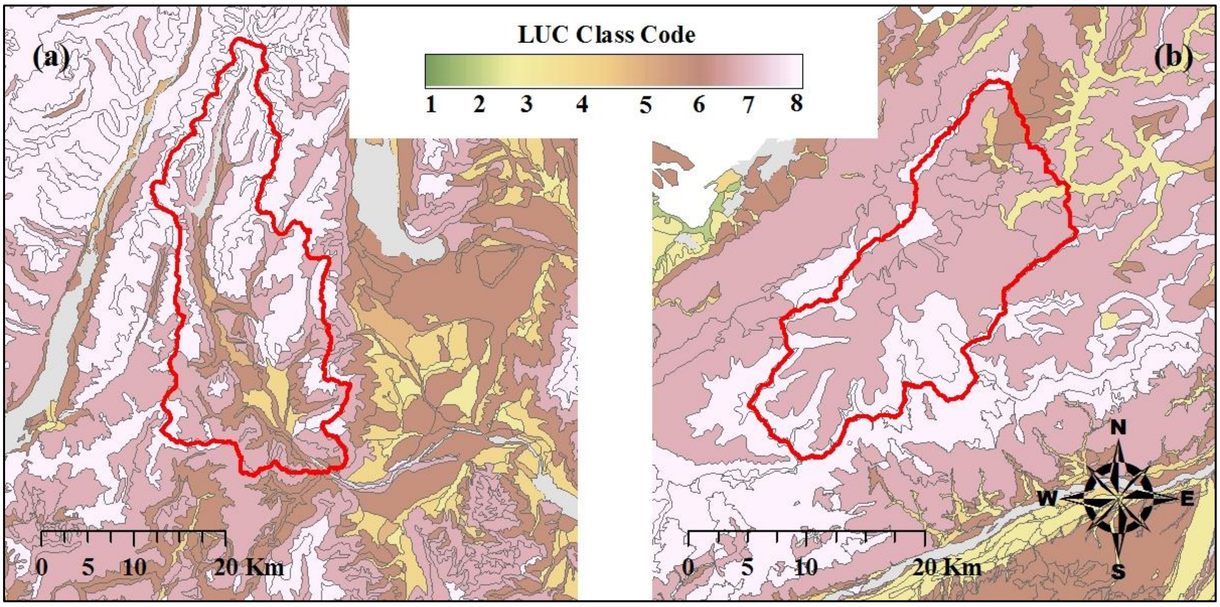


Figure 3-14: Land Use Capability (LUC) of the (a) Ahuriri and (b) Pelorus River catchments (LRIS, 2012)

To reduce complexity in the modelling of land use change a parameter multiplier was applied to the appropriate parameters in each subcatchment considered susceptible to land use change. The parameter multiplier was calculated so that the average values of the modified parameters represented the future scenario (Table 3-6). Hence, the spatial structure of the model was not modified *per se*; rather the parameters assigned to the existing land use scenario were modified so that they were more representative of a future land use scenario. Take, for example, the canopy storage capacity: if the average value of canopy storage capacity was approximately equal to 3 mm, indicating plantation forest or indigenous vegetation, the parameter multiplier would be 0.33 to give an average canopy storage capacity of 1 mm and reflect a change to agricultural land use.

Table 3-6: TopNet model parameters assigned on the basis of land cover type (Woods et al., 2009)

Land Cover Type	Canopy Storage Capacity (mm)	Canopy Evaporation Enhancement Factor
Plantation Forest	3	2
Indigenous Vegetation	3	2
Scrub and Unmanaged Areas	1	1
Agricultural and Horticultural Surfaces	1	1
Tussock (Campbell & Murray, 1990)	0.6	1
Bare and Impervious Surfaces	0	1

The values in Table 3-6 agreed with the findings of past investigations, which suggested that there is no significant difference in canopy water storage capacity between plantation forest and indigenous vegetation or forest, and that a canopy storage capacity of 3 mm is reasonable for a mature forest. Furthermore, a number of investigations have found little difference between the canopy storage capacity of scrubland, low-input agricultural land, and irrigated agricultural land (Rowe et al., 2002).

Saturated hydraulic conductivity K_S has been considered one of the most influential model parameters when considering flood peaks (Woods et al., 2009). It is generally accepted that forested land will have a higher K_S than grassland or pasture; however the difference in K_S between land cover types can vary. Some studies have found that K_S for forested land can be up to an order of magnitude greater than that of agricultural land (Karvonen, et. al., 1999; Lal, 1996) . Furthermore, managed agricultural land can display K_S double that of unmanaged grassland and rangeland (Halabuk, 2005). The clearing of forest in preparation for agricultural conversion, deemed ‘pre-pasture’, which is analogous to clearfelling and harvest of plantation forestry, had a very high K_S immediately after the removal of forest cover, but this was expected to decrease significantly once the soil was given time to adjust to the new land cover conditions (Zimmermann, Elsenbeer, & De Moraes, 2006). Each subbasin in the TopNet models had a value for K_S based on soil and land cover data. To modify K_S to reflect land use change, the parameter multiplier was changed to change K_S in each subbasin by a reasonable amount, analogous to calibrating the parameter. The parameter multipliers that were applied to K_S in the simulation of land use changes in the Ahuriri and Pelorus River catchments are described in Table 3-7 and were determined based on the expected effect each scenario would have on K_S from past studies. K_S is also heavily dependent on soil properties, so further investigation is recommended to ensure the soil properties used in the development of the TopNet models accurately reflect the actual soil properties in the Ahuriri and Pelorus River catchments.

Table 3-7: Changes to K_S to reflect land use change

Land Use Change	Change in Saturated Hydraulic Conductivity K_S
Tussock Grassland to Native Forest	Increase by 500% in affected subcatchments
Tussock Grassland to Pasture	Increase by 100% in affected subcatchments
Native Forest to Pasture	Reduce by 50% in affected subcatchments
Exotic Forest to Bare Land	Reduce by 75% in affected subcatchments

To assess the sensitivity of the catchments to the extent of land use, the model was changed to simulate a moderately extensive land use and a more extensive land use change, which was approximately twice the extent of the moderate land use scenario. Previous studies have suggested that more extensive land use change would have a greater effect on the flood hydrology of the catchment. This allowed the sensitivity of each catchment to the area of land use change to be assessed. The extent of each scenario is shown in Figure 3-15, Figure 3-16, and Figure 3-17, and the proportion of each catchment affected by the change in land use is shown in Table 3-8. It should be noted that both scenarios in the Ahuriri River catchment were modified to the same extent, while the extent of the two scenarios in the Pelorus River catchment were different. It is not unreasonable to expect reforestation and conversion to agriculture in a catchment to cover a similar area, while forest harvest and clearfelling usually occurs over a lesser area.

Table 3-8: Area of catchment affected by proposed land use change scenarios

Land Use Change Scenario	Per cent of Catchment Affected
Moderate native reforestation or moderate conversion to pasture in Ahuriri	22%
Extensive reforestation or extensive conversion of tussock grassland to pasture in Ahuriri	40%
Moderate clearfelling and forest harvest in Pelorus	14%
Extensive clearfelling and forest harvest in Pelorus	28%
Moderate conversion of forest to pasture in Pelorus	23%
Extensive conversion of forest to pasture in Pelorus	42%

Once the models were modified for each land use change, the nine events that were previously run in each catchment were modelled for the potential land use scenarios (Table 3-4). This allowed the effect of land use change across each catchment to be quantified using a range of different flood magnitudes. It was expected that the model predictions for the unmodified catchment would differ from the observed flood flows due to inherent error in the model and potential error due to the rainfall input. Hence, relative change in peak flows due to land use change was the primary outcome of this modelling exercise. This allowed for conclusions to be drawn in relation to different event magnitudes and the influence that land use change may be expected to have. The model outputs from the scenarios were compared to previous studies to help to determine whether the predictions were reasonable.

The determination of a suitable value for hydraulic conductivity K_S was the most subjective of the three key parameters used to reflect land use change in the model. While the parameter multiplier used to change K_S to reflect land use change described in Table 3-7 appeared reasonable when compared to the existing literature, past studies have expressed a wide range of K_S values that could be used to accurately model different land covers (Halabuk, 2005; Karvonen et al., 1999; Lal, 1996; Zimmermann et al., 2006). Furthermore, K_S can be dependent on soil properties within a catchment as well as land cover. Hence, a simple sensitivity analysis was conducted to determine if the TopNet model predictions were significantly influenced by K_S. Only one scenario in the Ahuriri River catchment was used in the sensitivity analysis and it was expected that the results of the analysis would be applicable to each scenario in both catchments. The scenario predicting the effects on the flood hydrology following the conversion of tussock grassland to pasture over 40% of the catchment was used. The canopy storage capacity and canopy evaporation enhancement factor were set to reflect land use change, as outlined in Table 3-6. The sensitivity analysis considered three values for K_S: the original K_S value assigned to the current Ahuriri River catchment model, the K_S used in this study to reflect the land use change scenario, and a 200% increase from the original K_S (Table 3-9). These were obtained by leaving the parameter multiplier for K_S unchanged, and increasing the parameter multiplier for K_S by a factor of two and three, for each section of the analysis, respectively. In physical terms, K_S for each subbasin was left unchanged from the original, calibrated model for the current land use scenario. Following this, increasing the parameter multiplier for K_S by 100% and 200% resulted in the calibrated K_S for each subbasin increasing by 100% and 200%, respectively. A more thorough sensitivity analysis of the effect of K_S fell outside the scope of this research project; however the analysis was expected to give a useful indication of the significant of K_S to the flood peaks predicted by the TopNet.

Table 3-9: K_S used in sensitivity analysis of the TopNet model in the Ahuriri River catchment

Land use change scenario	Change in K_S to use for sensitivity analysis	Notes
Conversion to pasture over 40% of Ahuriri River catchment	No change from current scenario	No change to K_S from the original values for each subbasin, only employing the new canopy storage capacity and evaporation enhancement factor to reflect land use change
	Increase parameter multiplier by 100% in affected subcatchments	K_S used in this research project for the modelling of this scenario
	Increase parameter multiplier by 200% in affected subcatchments	Change in K_S due to land use change twice as large in order to determine model sensitivity

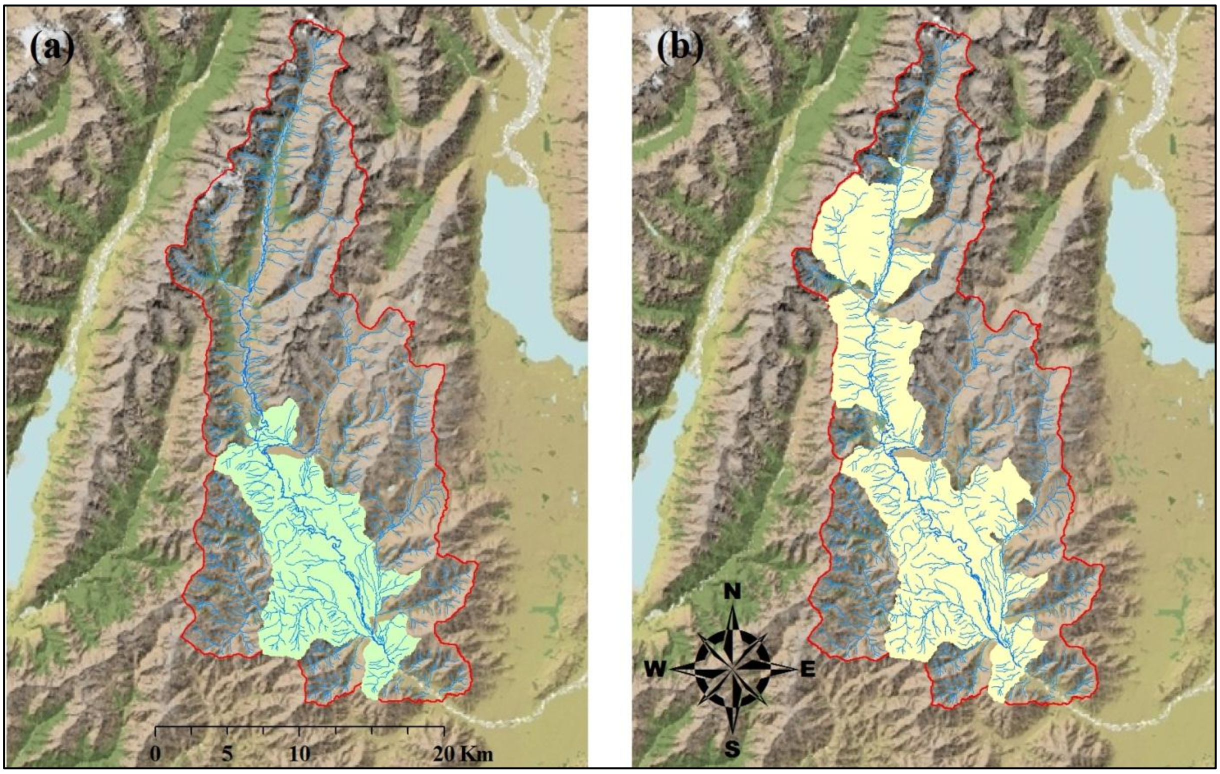


Figure 3-15: (a) 22% and (b) 40% native reforestation or conversion to pasture in the Ahuriri River catchment

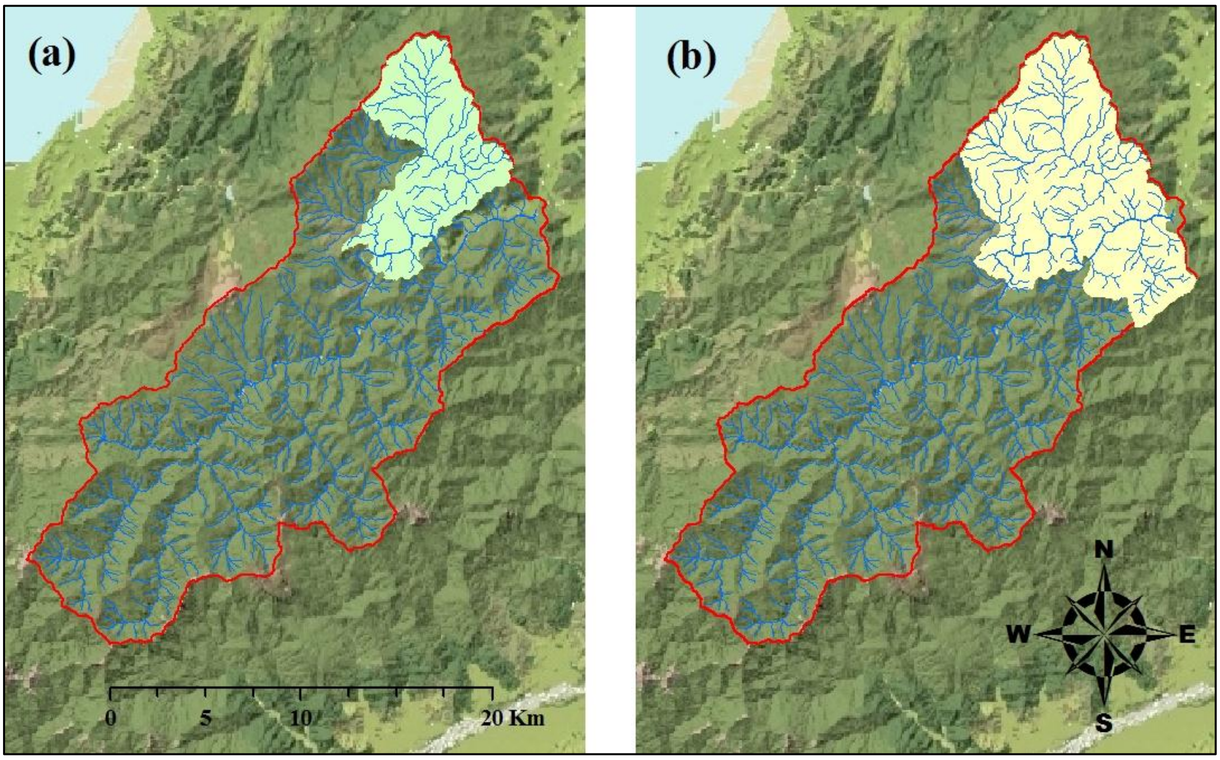


Figure 3-16: (a) 14% and (b) 28% forest harvest in the Pelorus River catchment

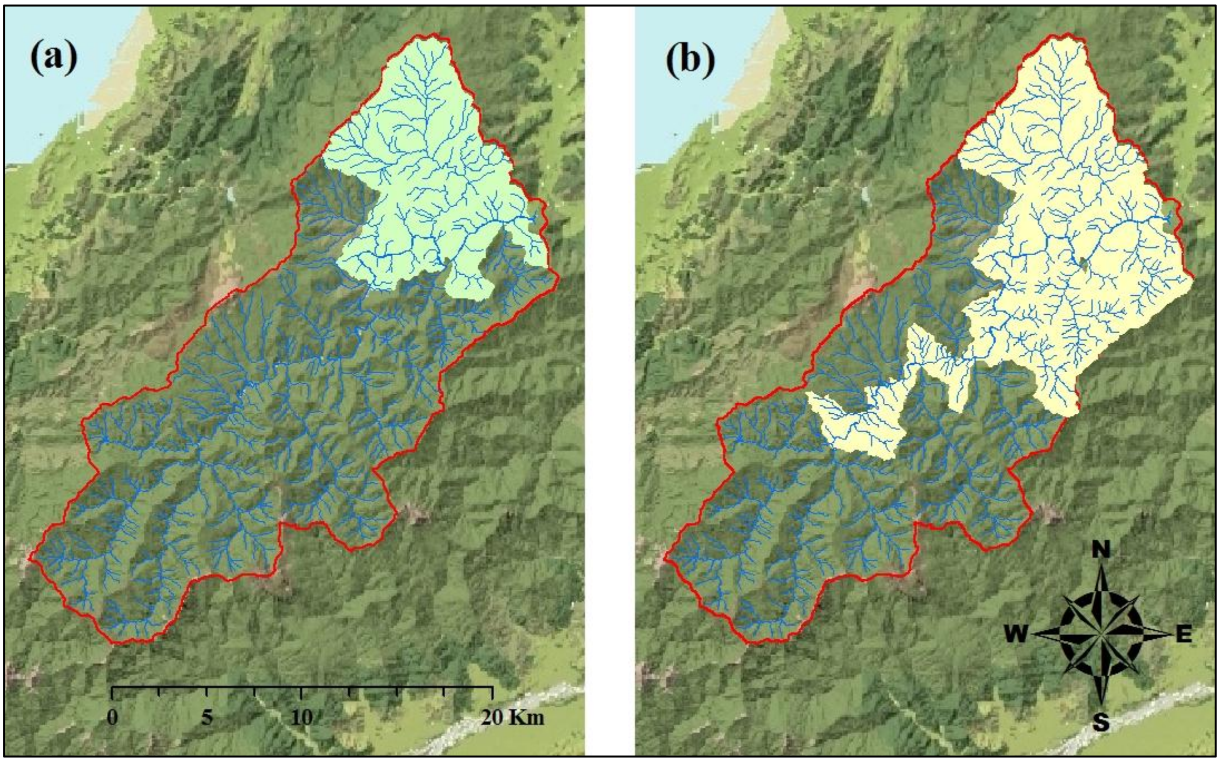


Figure 3-17: (a) 23% and (b) 42% conversion to pasture in the Pelorus River catchment

4 Results and Discussion

This section presents the results and discussion of each phase of the research project: testing the ability of the TopNet models for the Ahuriri and Pelorus River catchments to predict flood flows; running a selection of flood events in each catchment; and predicting the effect of land use change on the flood hydrology of each catchment using the TopNet model. A discussion of the potential application of the TopNet model for flood and land use management is also included.

4.1 Testing the TopNet Models for Flood Flow Prediction

TopNet is a continuous hydrologic model, hence was not specifically intended for the modelling of high flow events. This was reflected in the long calibration and validation time periods used when developing the model, although some focus was given to the accurate prediction of peak flows. Despite this, the model may prove to be a useful tool in predicting high flow events on a short timescale.

4.1.1 Ahuriri River Catchment Model

The three events used in the evaluation of the model for the Ahuriri River catchment are outlined in Table 3-2. The results are presented as a comparison of the observed hydrograph and the modelled hydrographs, using both stochastic rainfall disaggregation and station-based rainfall disaggregation (Figure 4-1, Figure 4-3, and Figure 4-5), which allowed the ability of the model to predict flood flows to be assessed and also the effect rainfall input had on the model predictions to be assessed. The NSE was calculated, as was the TPE and the PEPF (Table 4-1). The observed rainfall hyetograph, taken to be the average of the recorded rainfall from the two gauge stations in the catchment, and the rainfall input provided by the VCSN across the catchment were compared in order to identify the rainfall input as a potential source of error in the model predictions.

The observed and predicted hydrographs for the January 1994 event, the largest on record, are shown in Figure 4-1. Initial inspection of the hydrographs suggested that the TopNet model developed for the Ahuriri River catchment predicted the runoff hydrograph with a high level of accuracy, and that the hourly disaggregation of the daily rainfall estimate provided a more accurate flow prediction than the daily rainfall input disaggregated into hourly rainfall stochastically. The NSE values were 0.86 for both model predictions. This was well above the threshold of 0.70 suggested by Bandaragoda et al. (2004). The TPE for each model prediction was 1 hour or less, suggesting a very accurate prediction of channel flow and residence time. R_b for the model predictions made using the stochastic disaggregation of daily rainfall and station-based disaggregation of daily rainfall was −8.4% and −10.5%, respectively. This indicated that bias may be significant and may influence the NSE. The most significant error in this model simulation was the error in peak flow prediction for the model using stochastic disaggregation of daily rainfall. The PEPF showed that the model under-predicted peak flow by 16.8%, compared to a 2.2% over-prediction when the model employed station-based rainfall disaggregation.

Table 4-1: Results of model testing for the Ahuriri River catchment

Flow Event	9 Jan 1994	16 Nov 1999	19 Sep 2002
Peak Flow	568 m^3/s	371 m^3/s	291 m^3/s
ARI (Caruso et al., 2013)	43 years	7.9 years	3.7 years
Modelled with Stochastic Rainfall Disaggregation			
Peak Flow	472 m^3/s	276 m^3/s	130 m^3/s
NSE	0.86	−0.18	0.15
Relative bias R_b	−8.4%	13.3%	−23.2%
TPE	0 hours	22 hours	1 hour
Peak flow error	−95.7 m^3/s	−95.2 m^3/s	−161.1 m^3/s
PEPF	−16.8%	−28.2%	-55.4%
Modelled with Station-based Rainfall Disaggregation			
Peak Flow	581 m^3/s	298 m^3/s	206 m^3/s
NSE	0.86	0.27	−0.33
Relative bias R_b	−10.5%	2.7%	−6.1%
TPE	1 hour	24 hours	15 hours
Peak flow error	12.7 m^3/s	21.7 m^3/s	−85.2 m^3/s
PEPF	2.2%	6.4%	−29.3%

The VCSN predicted a spatially-averaged depth of rainfall across the catchment of 239mm. This is 32% higher than the observed rainfall data, which recorded an average of 181mm between the two active rainfall gauge sites. From visual inspection of the hyetographs (Figure 4-2) it was clear that the station-based hourly disaggregation of VCSN rainfall prediction reflected the observed rainfall reasonably well. The stochastic disaggregation of the rainfall input was less accurate, although the time and magnitude of some hourly rainfall, such as the peak rainfall on 09/01/1994, correlated well with the observed data.

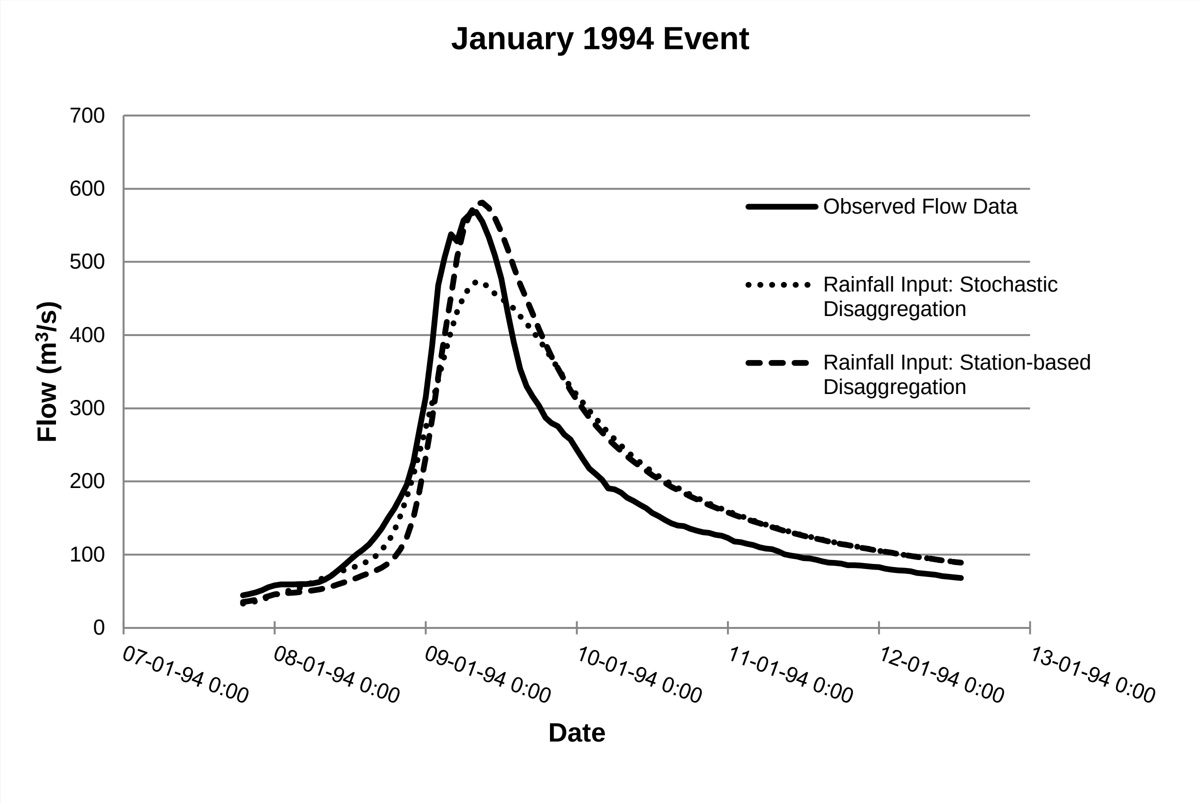


Figure 4-1: Observed and predicted hydrographs for the January 1994 event, Ahuriri River

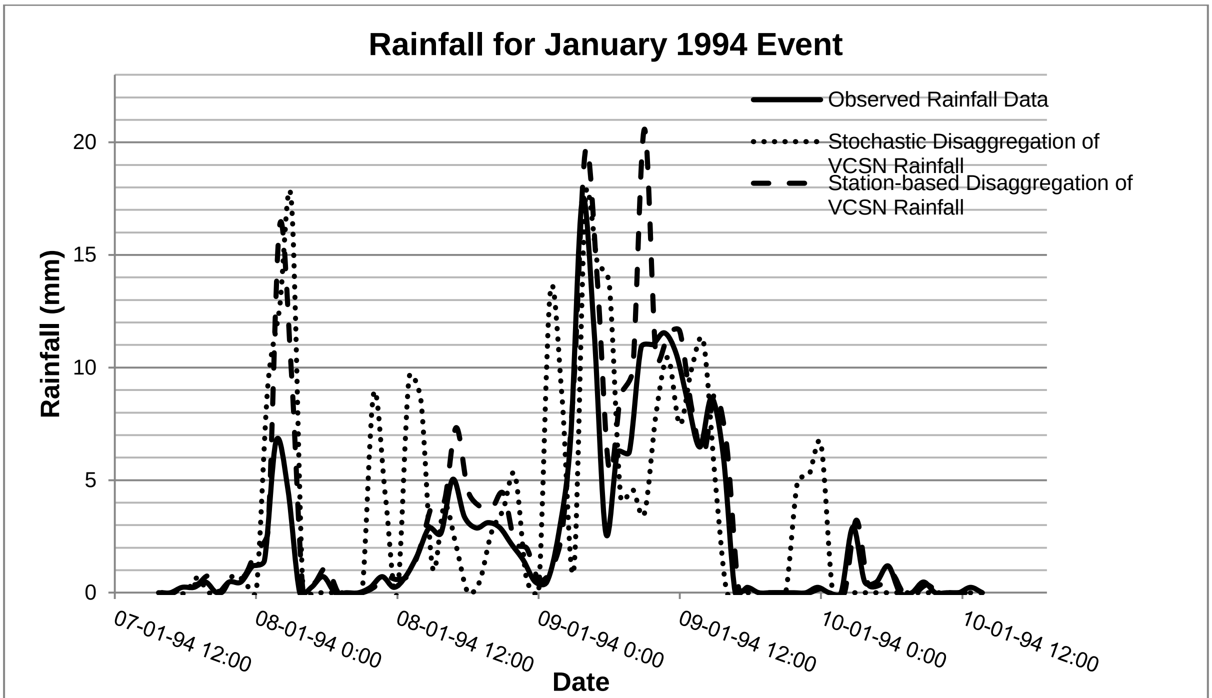


Figure 4-2: Spatially-averaged rainfall hyetograph for January 1994 event, Ahuriri River catchment

The November 1999 event was smaller than the January 1994 event and displayed a double-peaked hydrograph. The model predictions were, upon initial visual inspection, less accurate (Figure 4-3). The NSE values for the model predictions were −0.18 and 0.27 for the model using stochastic disaggregation of daily rainfall and station-based disaggregation of daily rainfall, respectively. R_b was 13.3% and 2.7%, respectively, which indicated the model prediction made using stochastic disaggregation of daily rainfall as the rainfall input displayed significant bias that may have influenced NSE. For predictions made using stochastic and station-based rainfall disaggregation, the TPE and PEPF were 22 hours and -22.8%, and 24 hours and 6.4%, respectively.

The average of the observed rainfall between the rainfall gauge stations for the November 1999 event was 211mm. The VCSN predicted a slightly higher rainfall of 222mm averaged across the Ahuriri River catchment, which was 5.2% more than the observed rainfall. The stochastically disaggregated rainfall input provided the model with higher peak hourly rainfall for several hours throughout the storm event than the observed rainfall signal, but also predicted zero rainfall for a period during 15/11/1999. The station-based rainfall disaggregation displayed a similar signal to the observed data, with the exception of an over-estimate of rainfall peaks during 16/11/1999.

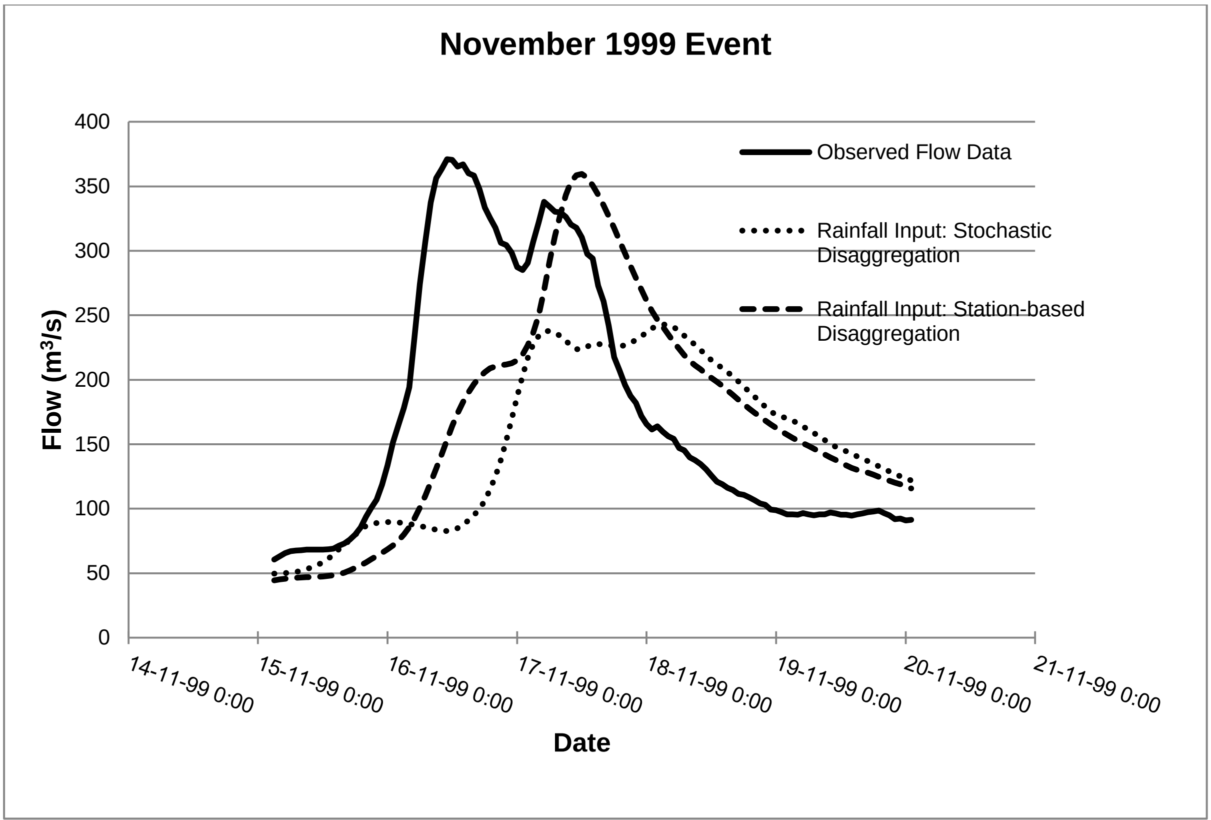


Figure 4-3: Observed and predicted hydrographs for the November 1999 event, Ahuriri River

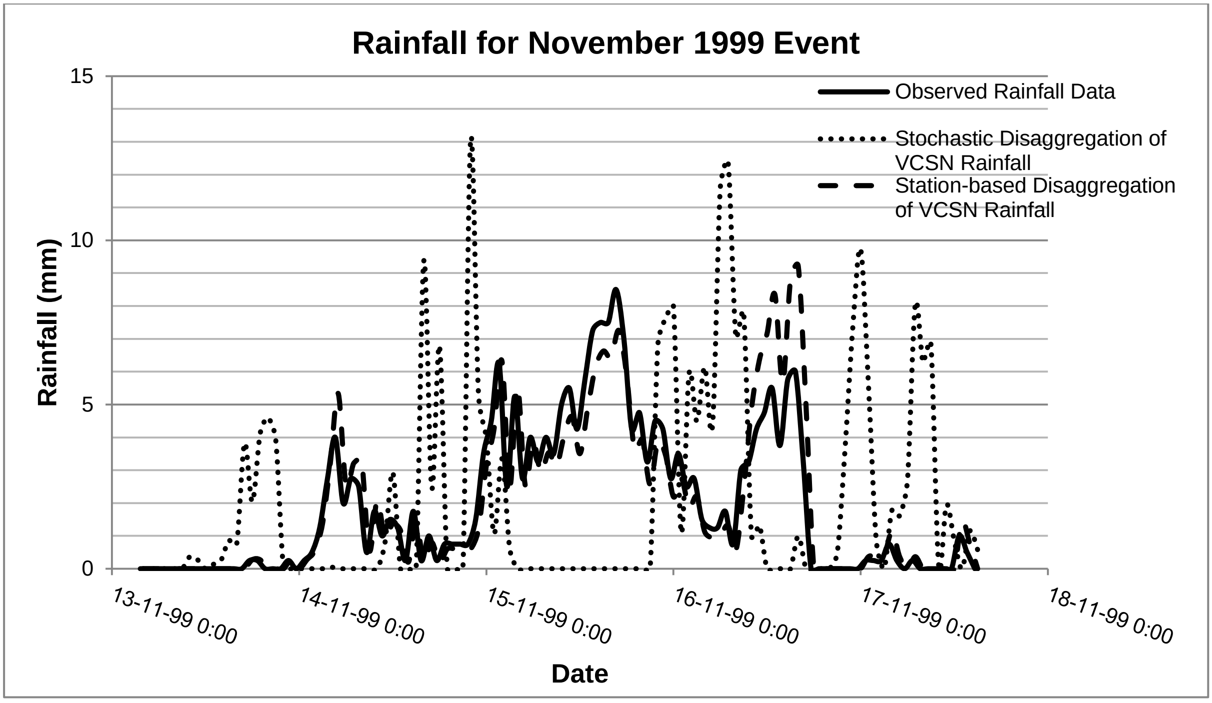


Figure 4-4: Spatially-averaged rainfall hyetographs for November 1999 event, Ahuriri River catchment

The September 2002 event was the smallest event used to test the accuracy of the Ahuriri River catchment model, with an ARI of 3.7 years. The observed hydrograph displayed a step-wise rising limb, which added complexity to the event. From initial inspection, it was clear that the model did not accurately predict the flood flow for the event. This is supported by low NSE values of 0.15 and −0.33 for the model when using stochastic and station-based disaggregation of daily VCSN rainfall into an hourly rainfall input, respectively. R_b was −23.2% and −6.1%, respectively. The significant bias in both predictions may have influenced NSE. For predictions made using stochastic and station-based rainfall disaggregation, the TPE and PEPF were 1 hour and -55.4%, and 15 hours and −29.3%, respectively.

The net rainfall observed across the catchment for the September 2002 event, taken as the average of the observed rainfall from the two active precipitation gauges, was 145mm. The VCSN predicted 173mm across the catchment, an overestimate of 19.3%. The station-based hourly disaggregation of VCSN daily rainfall correlated reasonably well to the observed rainfall signal, although the volume of rainfall early in the storm event, after 00:00 on 18/09/2002 was under-predicted and peak rainfall later in the event, after 12:00 on 19/09/2002 was over-predicted (Figure 4-6). The stochastic disaggregation of VCSN rainfall did not correlate well with the observed rainfall hyetograph (Figure 4-6).

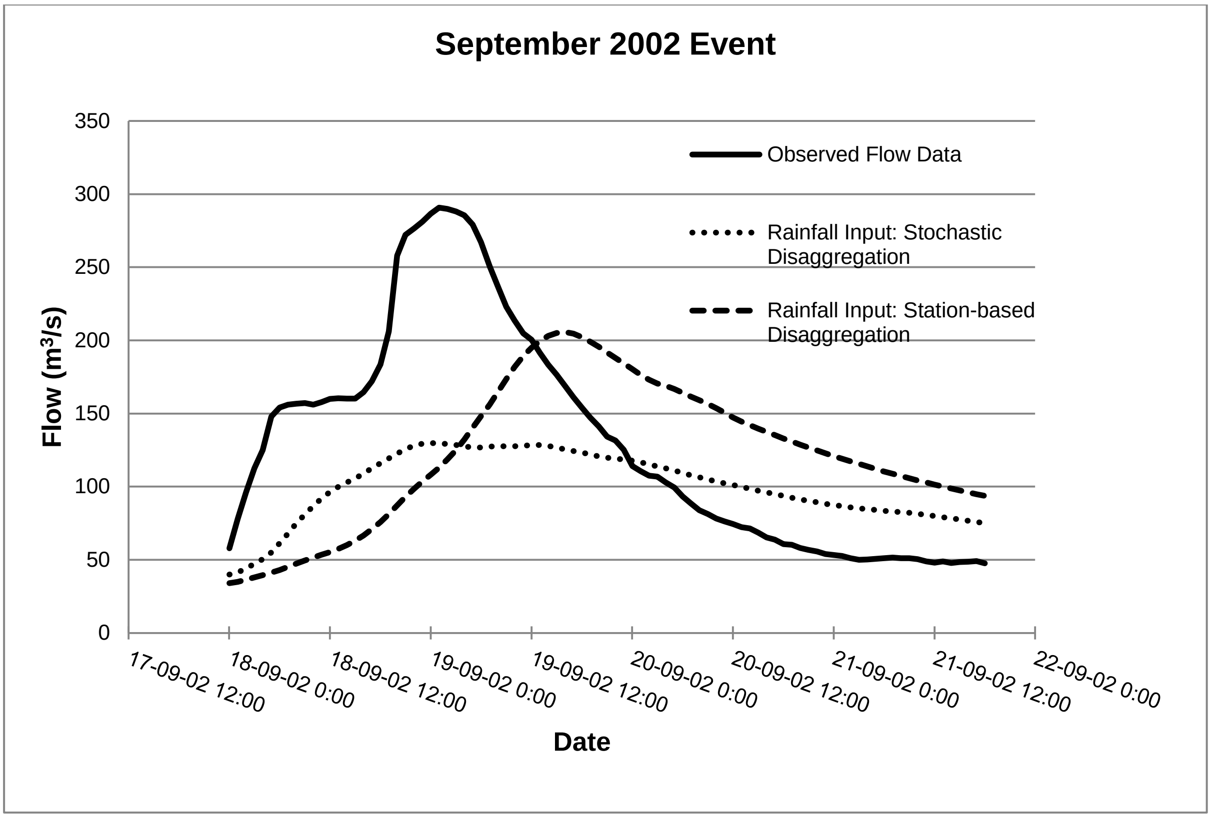


Figure 4-5: Observed and predicted hydrographs for September 2002 event, Ahuriri River

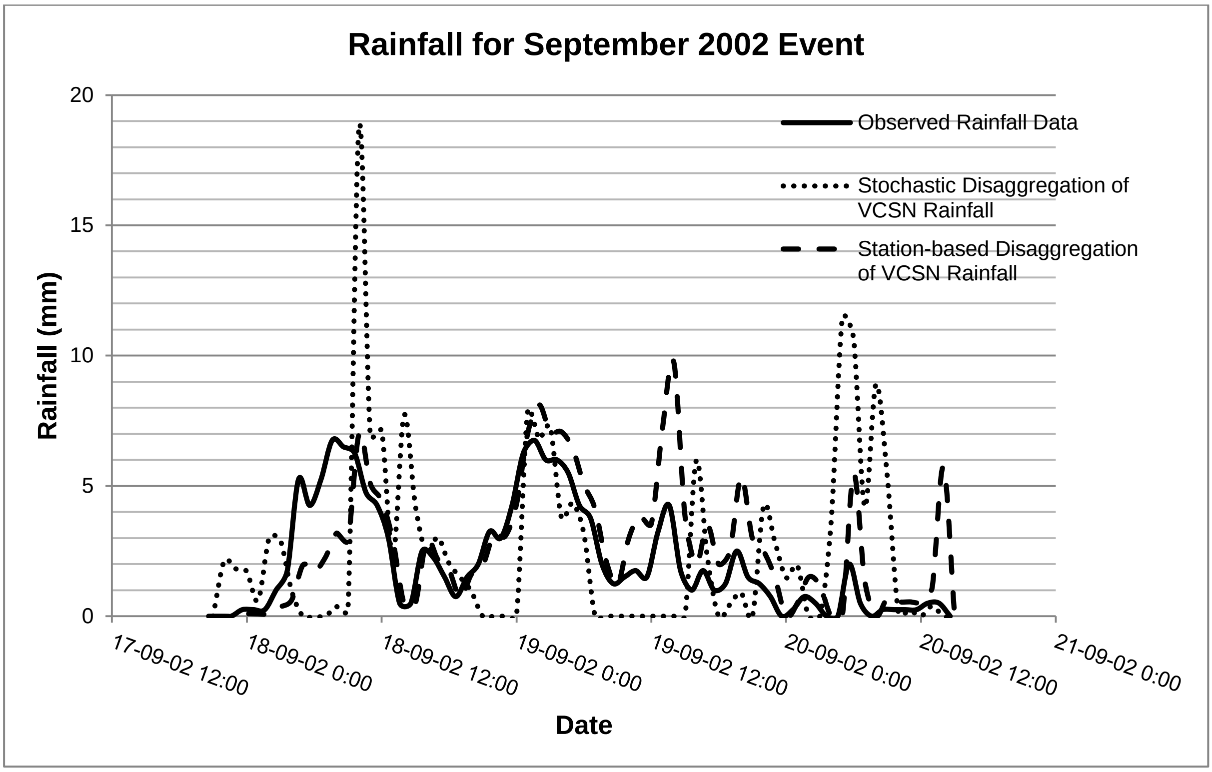


Figure 4-6: Spatially-averaged rainfall hyetographs for September 2002 event, Ahuriri River catchment

The period over which the model was calibrated was modelled to assess the calibration of the model and evaluate the model for a longer-term water balance. This was the intended purpose of the model, and it was expected that the model would accurately predict the long-term hydrology of the catchment. Over the three-year period of June 1998 to May 2001, the predicted hydrographs for the model using both stochastic and station-based rainfall disaggregation had a NSE of 1.0 when compared to the observed flows. It was clear from comparing the observed and predicted hydrographs that there was error when predicting peak flows, but the model predicted near-average and below-average flows well (Figure 4-7). The NSE may have indicated such a strong correlation because the majority of the time period modelled showed typical or near-average flows, which were be expected to be modelled accurately given the original intent of the model developers. Furthermore, the cumulative discharge for the three-year period was predicted reasonable accurately by the model (Figure 4-8). Error in the cumulative model predictions using stochastic rainfall disaggregation and station-based disaggregation were 1.1% and 2.6%, respectively at the end of the three-year modelling period.

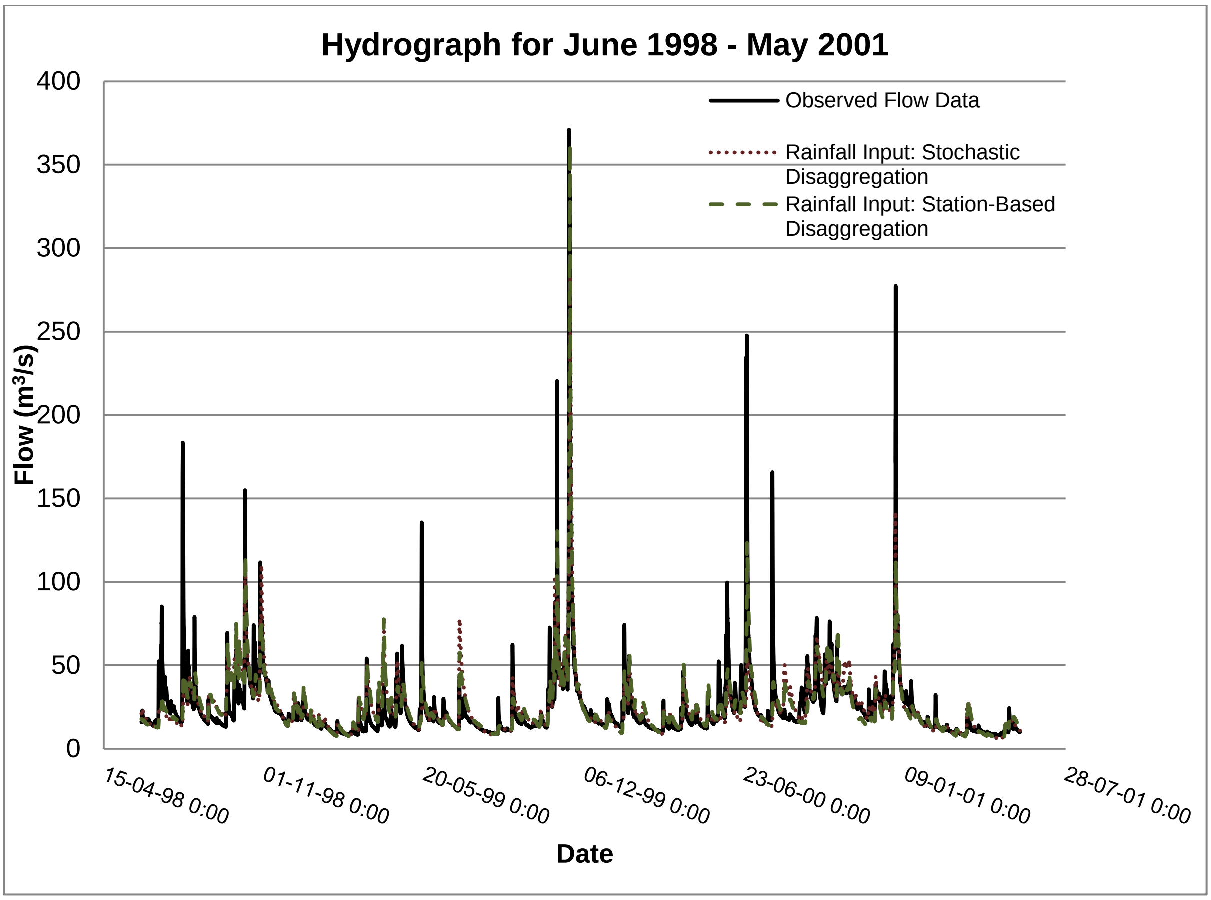


Figure 4-7: Observed and predicted hydrographs for the calibration period June 1998 to May 2001, Ahuriri River

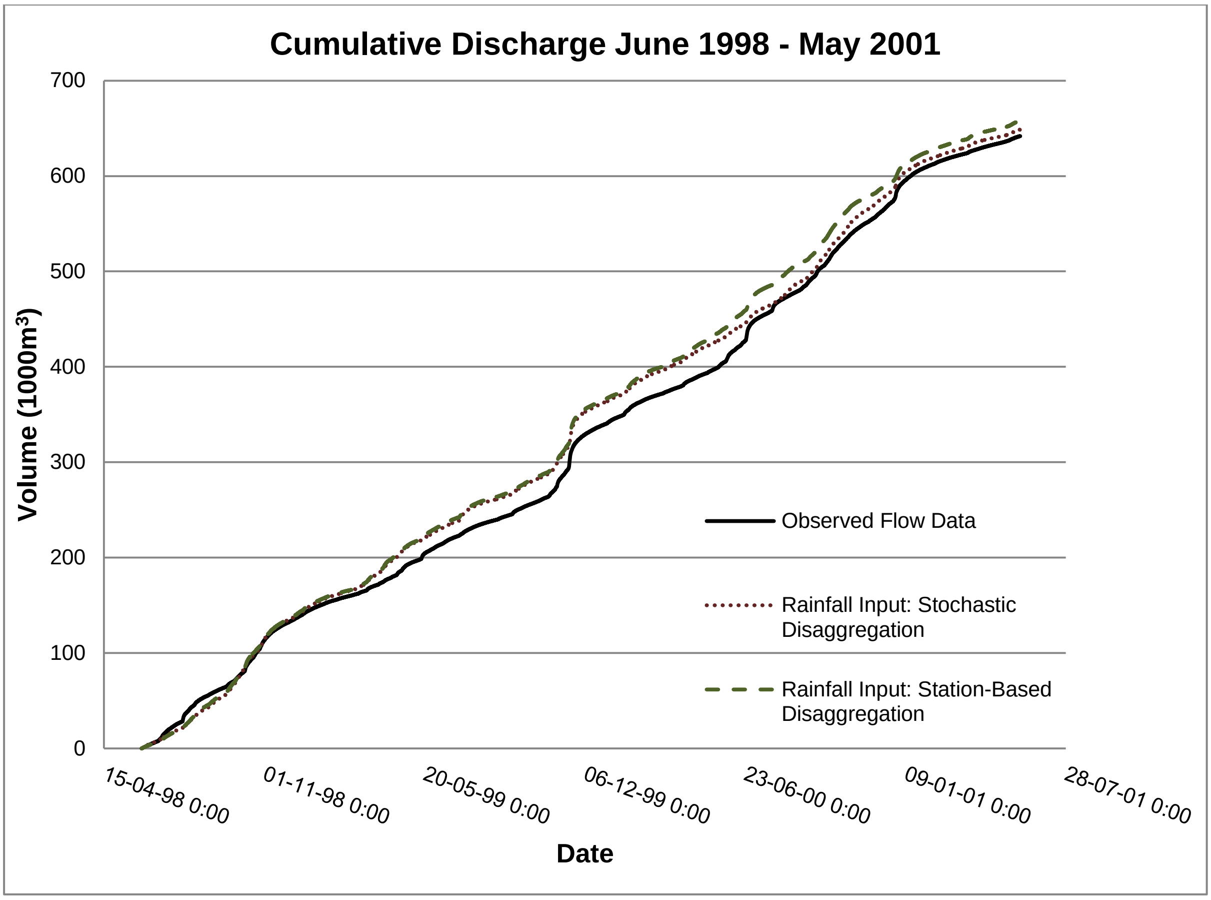


Figure 4-8: Observed and predicted cumulative discharge for the calibration period June 1998 to May 2001, Ahuriri River

4.1.2 Pelorus River Catchment

The three events used in the evaluation of the model for the Pelorus River catchment are outlined in Table 3-3. The results are presented as a comparison of the observed hydrograph and the modelled hydrographs, using both stochastic rainfall disaggregation and station-based rainfall disaggregation (Figure 4-9, Figure 4-11, and Figure 4-13), and summarised in Table 4-2. The estimated and observed rainfall for each event was compared and presented in Figure 4-10, Figure 4-12, and Figure 4-14. Furthermore, a longer water-balance was modelled for the period of model calibration and the hydrograph and cumulative discharges presented (Figure 4-15 and Figure 4-16).

Table 4-2: Results of model testing for the Pelorus River catchment

Flow Event	1 July 1998	23 Feb 1995	30 Jan 2000
Peak Flow	1667 m^3/s	1519 m^3/s	1366 m^3/s
ARI	21 years	18 years	9.3 years
Modelled with Stochastic Rainfall Disaggregation			
Peak Flow	1012 m^3/s	295 m^3/s	352 m^3/s
NSE	0.37	0.12	0.20
Relative bias R_b	-32.8%	−12.6%	-35.6%
TPE	−4 hours	−8 hours	−1 hour
Peak flow error	−654 m^3/s	−1225 m^3/s	−1014 m^3/s
PEPF	-39.2%	−80.6%	−74.2%
Modelled with Station-based Rainfall Disaggregation			
Peak Flow	805 m^3/s	433 m^3/s	405 m^3/s
NSE	0.57	0.42	0.34
Relative bias R_b	-32.8%	−8.3%	-33.7%
TPE	3 hours	2 hours	0 hours
Peak flow error	−861 m^3/s	−1087 m^3/s	−960 m^3/s
PEPF	-51.7%	−71.5%	−70.3%

The July 1998 event was the second-largest recorded high flow event, and displayed a relatively complex observed hydrograph due to the local peak after the large flood peak. Initial inspection suggested that the model did not accurately predict the peak magnitude or the occurrence of the peak flow (Figure 4-9). The NSE values were 0.37 and 0.57 for the model when using stochastic and station-based hourly disaggregation of daily rainfall, respectively, which suggested that the efficiency of the catchment model for predicting the flood event was poor. R_b was 32.8% for both model predictions, which suggested that bias was significant in the model. For predictions made using stochastic and station-based disaggregation of daily rainfall as an input, the TPE and PEPF were −4 hours and -39.2%, and 3 hours and -51.7%, respectively. This was evidence that the model significantly underestimated the flood peak for the July 1998 flood event on the Pelorus River.

The average total rainfall for the July 1998 event, from two rainfall gauge stations near the Pelorus River catchment, was 320mm. The VCSN predicted 301mm, which was 5.9% less than the observed rainfall. The station based disaggregation of the VCSN rainfall prediction correlated well with the observed rainfall signal. The distribution of the stochastically disaggregated VCSN rainfall input significantly overestimated the rainfall peak intensity around 12:00 on 01/07/1998 and underestimated the rainfall intensity between 00:00 and 12:00 on 02/07/1998 (Figure 4-10).

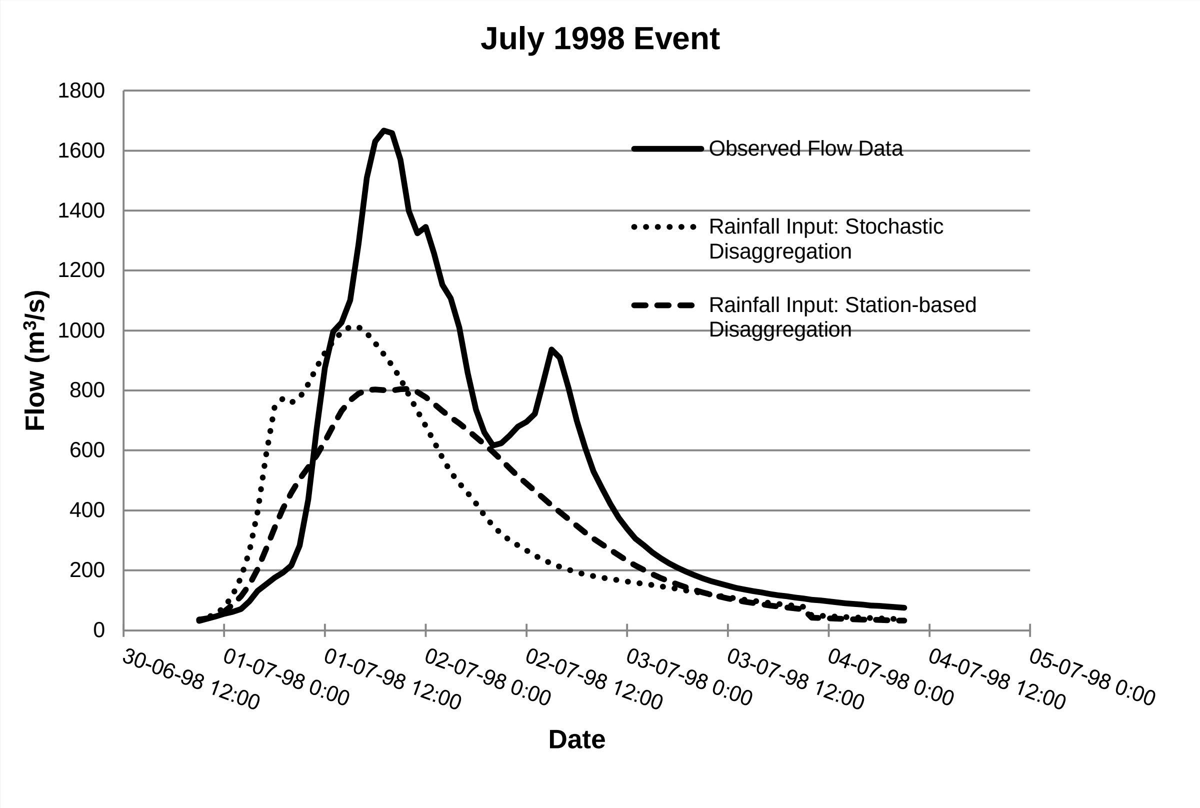


Figure 4-9: Observed and predicted hydrographs for the July 1998 event, Pelorus River

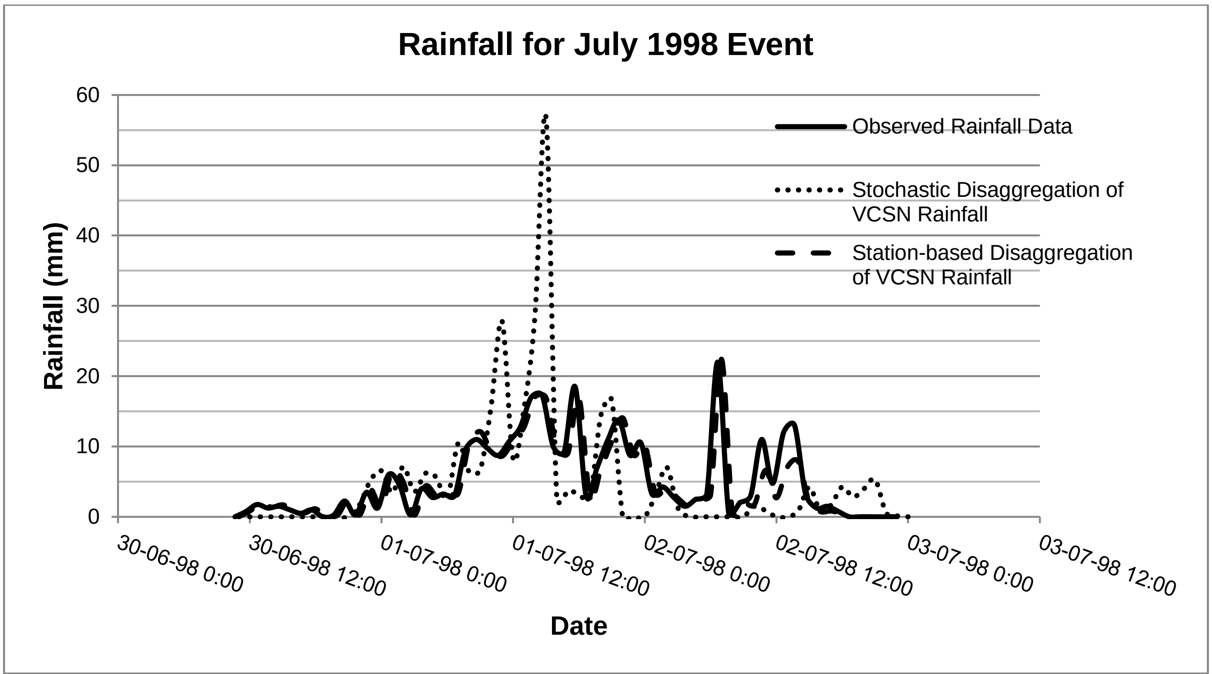


Figure 4-10: Spatially-averaged rainfall hyetographs for July 1998 event, Pelorus River catchment

The February 1995 event was the third-largest flow in the recorded period on the Pelorus River. From a visual inspection of the observed and predicted hydrographs, it was clear that there was significant error in the model prediction (Figure 4-11). The low NSE values of 0.12 and 0.42 for the hydrographs predicted using stochastic and station-based disaggregation of daily rainfall as a model input, respectively, also indicated significant error. R_b was −12.6% and −8.3%, respectively, which was significant and may have had some influence on NSE. PEPF was −80.6% and −71.5% for hydrographs generated using stochastic disaggregation of daily rainfall and station-based disaggregation of daily rainfall, respectively, indicating the model significantly under-predicted peak flow for the high flow event.

The average of the observed rainfall at three active gauging sites surrounding the Pelorus River catchment was 143mm over the duration of the storm. The VCSN predicted an average of 205mm across the catchment, an overestimate of 43%. The rainfall signal produced by stochastic disaggregation of the VCSN prediction differed markedly from the observed rainfall signal, with significantly higher rainfall intensity early in the storm and no rainfall where the observed data suggests rainfall should be at a peak. It is clear that the signal produced by station-based disaggregation of the VCSN rainfall correlates more closely to the observed rainfall, but overestimates peak rainfall intensity (Figure 4-12).

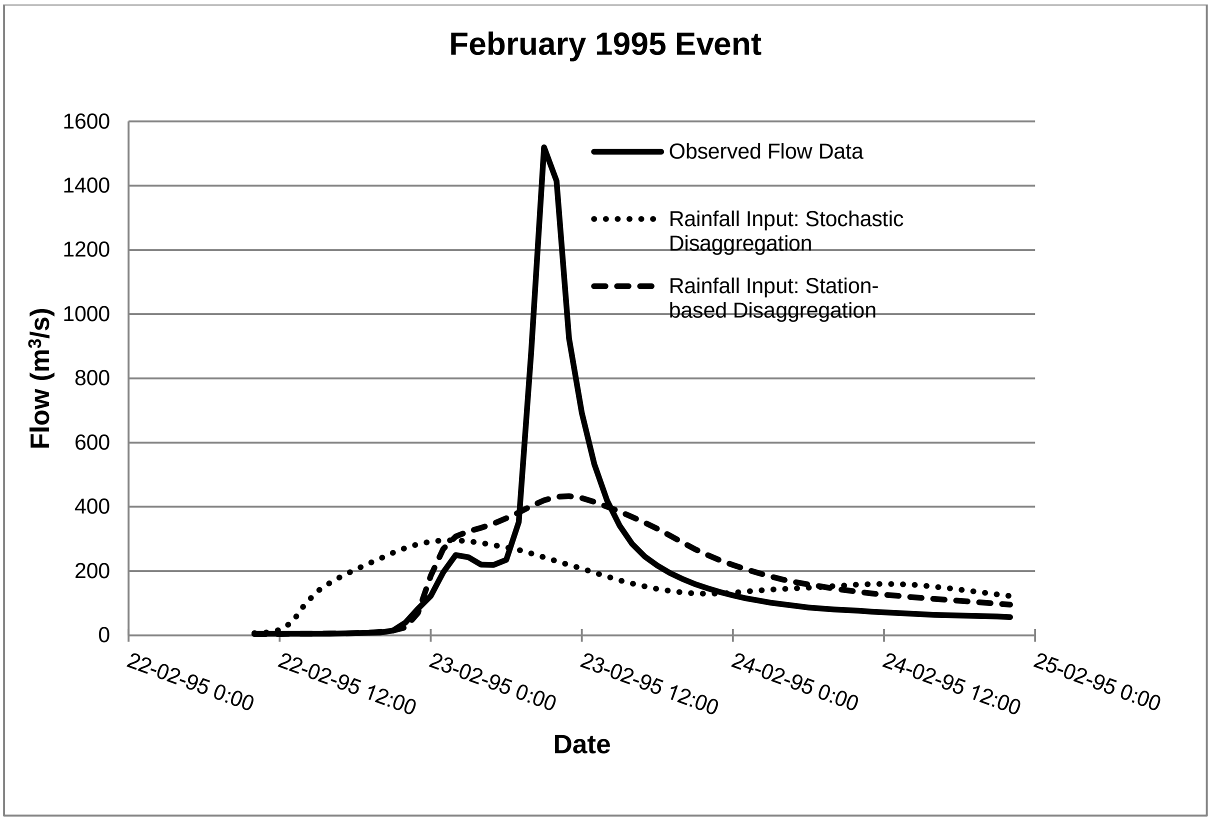


Figure 4-11: Observed and predicted hydrographs for the February 1995 event, Pelorus River

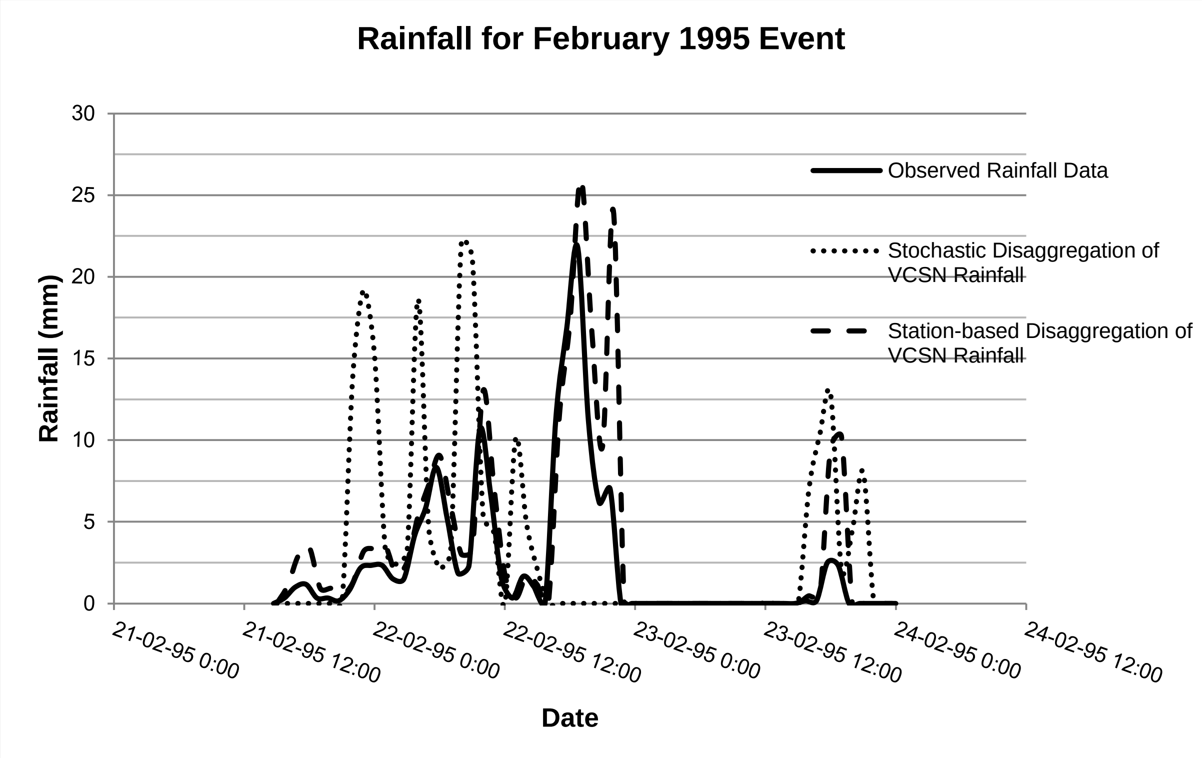


Figure 4-12: Spatially-averaged rainfall hyetographs for February 1995 event, Pelorus River catchment

The January 2000 high flow event was the smallest to be used in this model evaluation exercise and occurred over the shortest time period. As with the October 1983 event and the July 1998 event, there was significant error in the model prediction for peak flow in the Pelorus River (Figure 4-13). The NSE for the hydrograph predicted using stochastic disaggregation of daily rainfall was 0.20 and R_b was -35.6%. The NSE for the hydrograph predicted using station-based disaggregation of daily rainfall was 0.34 and R_b was -33.7%. The large values of R_b indicated that bias was significant in the model predictions. PEPF was −74.2% and −70.3% for hydrographs generated using stochastic disaggregation of daily rainfall and station-based disaggregation of rainfall, respectively, indicating that the model significantly under-predicted peak flows for this event.

The average of the observed rainfall data from three nearby stations recorded rainfall across the Pelorus River catchment contributing to the January 2000 event of 137mm over a 24-hour period. The VCSN predicted 151mm across the catchment, an overestimate of 10.2%. The rainfall input to the model based on station data correlated well to the observed rainfall signal. The input produced by stochastic disaggregation of VCSN rainfall did not correlate well, and overestimated peak rainfall early in the storm (Figure 4-14).

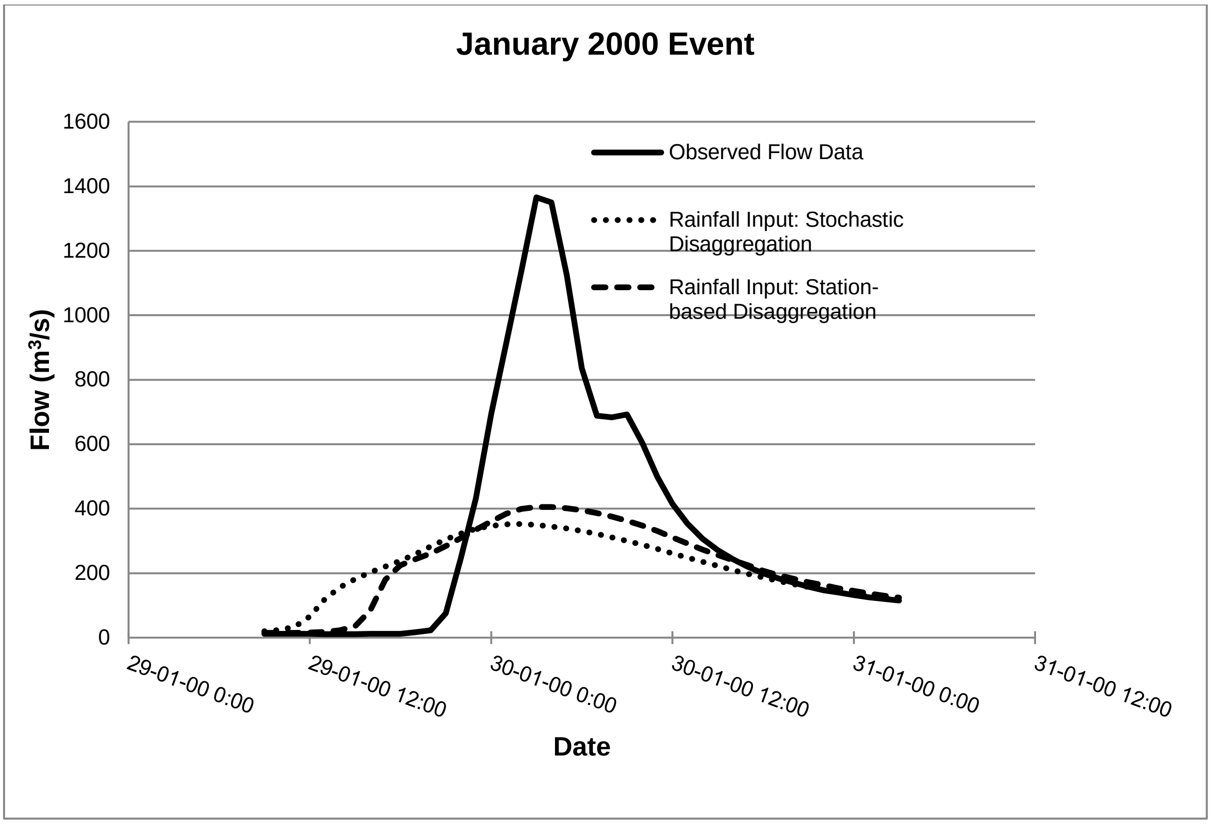


Figure 4-13: Observed and predicted hydrographs for the January 2000 event, Pelorus River

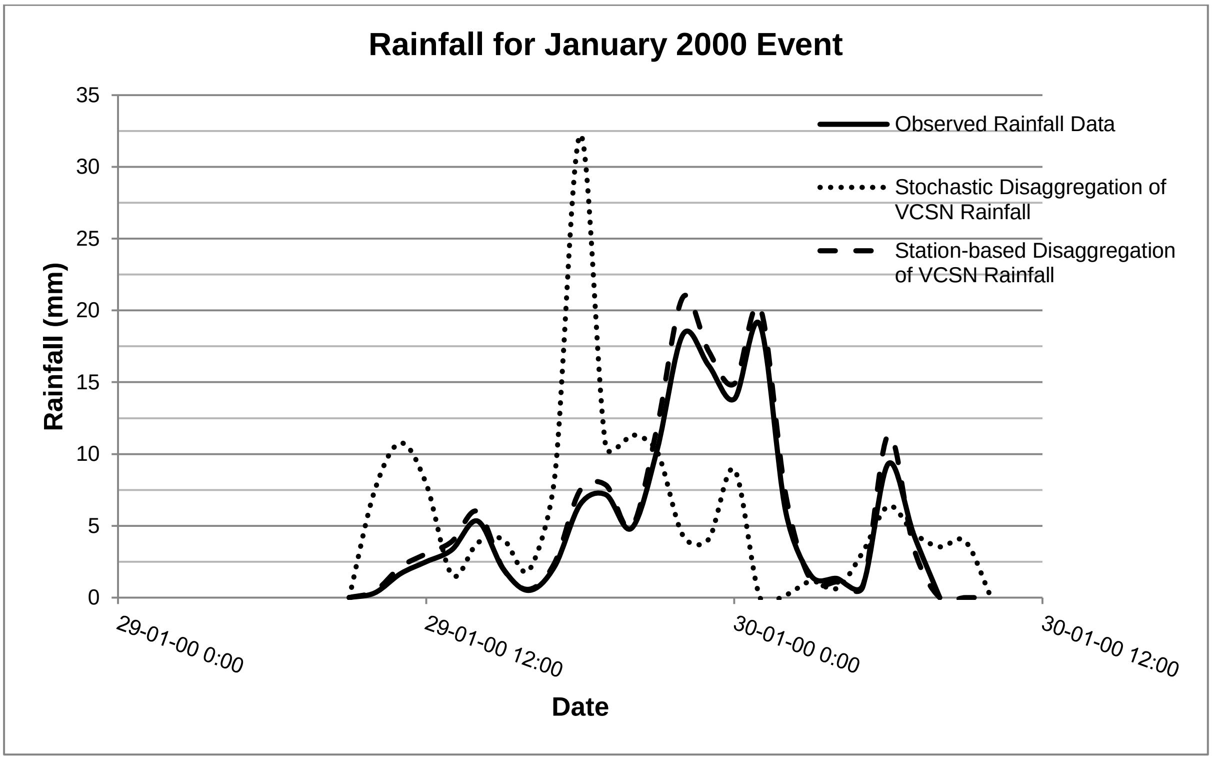


Figure 4-14: Spatially-averaged rainfall hyetographs for January 2000 event, Pelorus River catchment

As with the Ahuriri River catchment model, the time period over which the Pelorus River catchment model was calibrated was also modelled as part of the model test to assess the model for longer term water balance predictions and assess the calibration of the model. Over the three-year period from June 1998 to May 2001, the predicted hydrographs for the model using both stochastic and station-based disaggregation of daily rainfall had a NSE of 1.0. It was clear from observing the hydrographs that there was error when predicting peak flows, but the model predicted near-average and below-average flows well (Figure 4-15). Furthermore, the cumulative discharge for the three-year period was predicted reasonably accurately by the model; error in the cumulative model predictions using stochastic disaggregation of daily rainfall and station-based disaggregation of daily rainfall were 1.8% and 1.0%, respectively, over the three-year period.

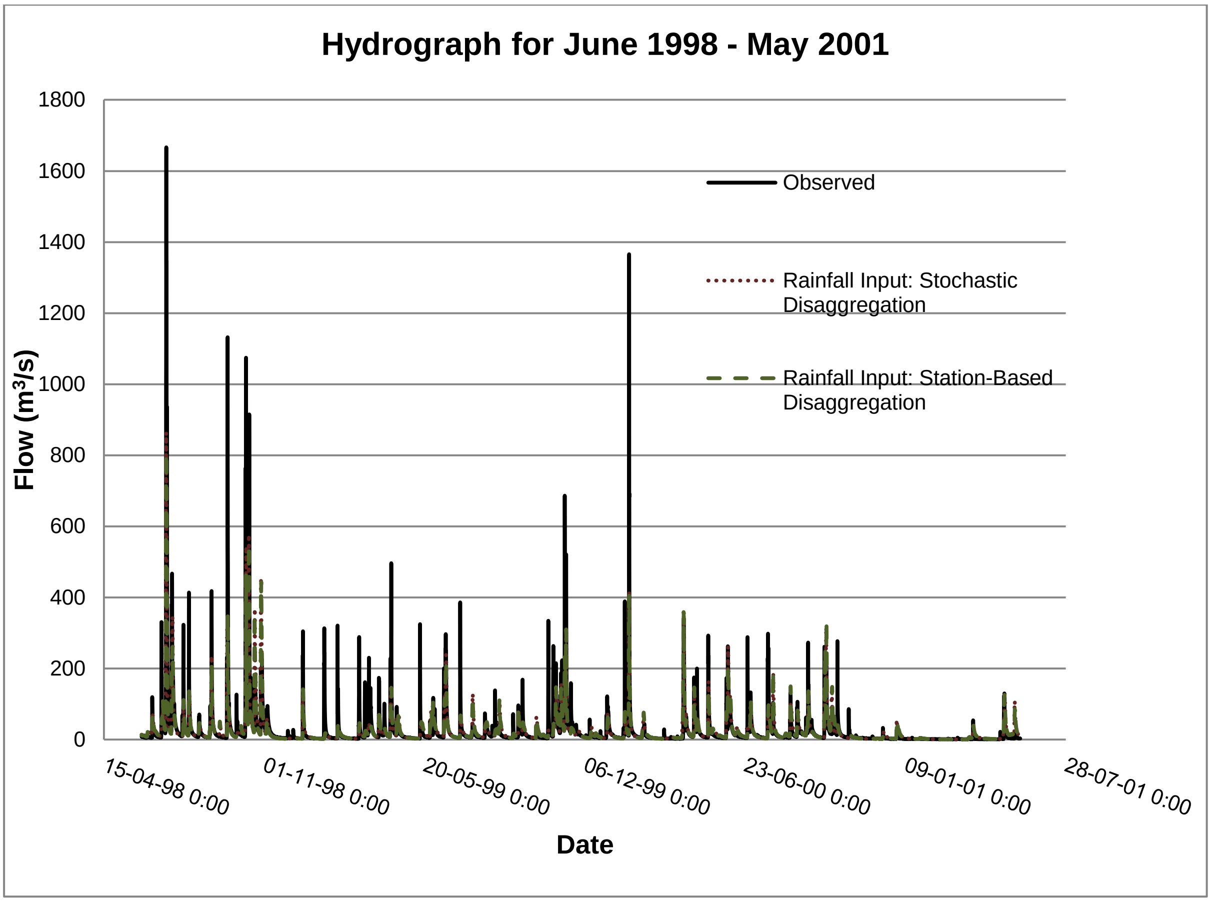


Figure 4-15: Observed and predicted hydrograph for the calibration period June 1998 to May 2001, Pelorus River

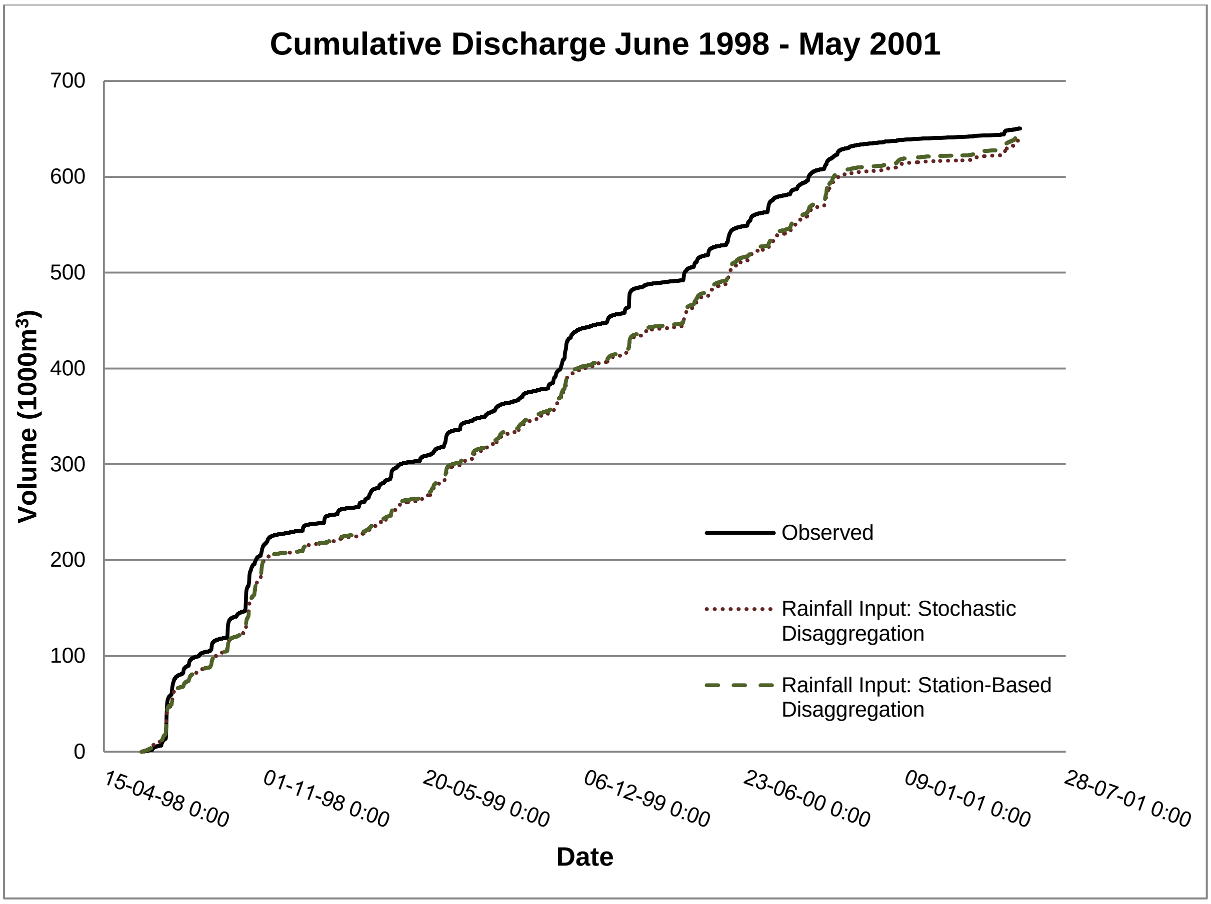


Figure 4-16: Observed and predicted cumulative discharge for the calibration period June 1998 to May 2001, Pelorus River

4.1.3 Discussion of Model Testing

Overall, the two catchment models appeared to predict larger flows with greater accuracy than smaller flows. The discernible trend from the three events in the Ahuriri River catchment was that the error, quantified by the objective functions, generally increased as the ARI of the modelled event decreased. However, this was not necessarily the case when considering the three events modelled in the Pelorus River catchment, where there appeared to be no correlation between error and event magnitude. While the value of the NSE for the larger flood prediction was better than the NSE for the smaller predictions, the NSE for all flood predictions in the Pelorus River indicated significant error. Furthermore, the error in the flow predictions on the Ahuriri River made using stochastic disaggregation of daily rainfall as the rainfall input to the model was generally larger than predictions made when daily rainfall was disaggregated based on observed station data. There appeared to be no similar trend for error in peak flow predictions in the Pelorus River catchment.

The NSE was generally closer to one for the modelled events on the Ahuriri River than for the modelled events on the Pelorus River. The magnitude of R_b was also generally less for the

Ahuriri River catchment model than for the Pelorus River catchment model. This suggested that the TopNet model for the Ahuriri River catchment predicted flood flows with greater accuracy, and this was supported by the smaller magnitude of PEPF in the predictions for the Ahuriri River catchment model. However, the large magnitude of R_b for the Pelorus River catchment model predictions suggested that the bias was more significant than in the Ahuriri River catchment model. R_b was negative for all simulations on the Pelorus River, indicating that the model had a propensity to underpredict flood flows in the Pelorus River catchment. For most simulations in both catchments, the magnitude of R_b was greater than 5%, which indicated that bias was significant in both models (McCuen et al., 2006). NSE may be sensitive to bias, and significant bias can cause a lower NSE value. Significant bias in the model may have caused the NSE to yield a low value, rather than poor model efficiency.

Error in spatial distribution, temporal distribution, or net volume of rainfall input to a hydrologic model can be responsible for significant error in the model predictions. Daily rainfall volume input to the model was provided by the VCSN. While the VCSN was the product of a relatively advanced method of estimating climate parameters, a method that has generally been considered appropriate, it is still subject to error (Tait et al., 2012). For the most part, error in rainfall interpolation has been attributed to insufficient actual climate data on which to base the VCSN. It was expected that the VCSN would produce greater error for larger rainfall events, especially for alpine regions above 500 m ASL (Tait et al., 2012). The Ahuriri River catchment and a significant area of the Pelorus River catchment are located above 500 m ASL. The error was evident in the comparison of the observed rainfall and the rainfall estimated from the VSCN in the Ahuriri River catchment, where the largest flood event of the three events considered, in January 1994, had the largest difference in observed and estimated total rainfall averaged across the catchment.

The majority of gauging stations supplying data to the VCSN are located below 500 m ASL, and as a result of this low-density network of stations the interpolated values for precipitation in the VCSN in alpine regions are likely to have higher error – in fact, some interpolated events in the VCSN may be based on storms that occurred outside the catchment, or some storms may be missed entirely (Tait et al., 2012). However, the Ahuriri River catchment is located within an alpine region with a relatively dense network of climate stations due in part to the significant HEP developments in the area. Conversely, the VCSN covering the Pelorus River catchment uses climate data from a typical sparse network of climate stations. Within a 100 km radius of the outflow of the Ahuriri River, there are approximately 40 climate stations that can provide current or historical data to the VCSN. Of these 40 stations, 15 were operational as of 2011, with the nearest located 14 km from the Ahuriri River outflow at an elevation of 488 m ASL. This station was one that contributed to the station-based disaggregation of daily rainfall estimates in the TopNet model and was located within the Ahuriri River catchment. The highest operational climate station within 100km of the Ahuriri River outflow was located 77 km to the northeast at an elevation of 762 m ASL. Approximately half of the operational climate stations within 100 km of the Ahuriri River had an elevation greater than 300 m ASL. By comparison, the Pelorus River also has approximately 40 current or historical climate stations within 100 km of its outflow, with 13 operational as of 2011. However, the nearest operational station was 22 km away at an elevation of 4 m ASL. The highest station within 100 km was located 78 km inland to the southeast and at an elevation of 634 m, and this was the only station within 100 km of the Pelorus River located above 300 m ASL (NIWA, 2012b). The stations used in the disaggregation of daily VCSN rainfall estimates for the Pelorus River catchment model did not contribute to the VCSN.

Hence, the error from the VCSN providing climate data to the Pelorus River catchment model was likely to be larger than error in the climate data estimated for the Ahuriri River catchment. This was supported by the comparison of the observed rainfall data and the estimated rainfall from the VCSN, which showed that the difference between the observed rainfall and the rainfall estimated by the VCSN for the Pelorus River catchment was larger than for the Ahuriri River catchment. The flood hydrographs generated by TopNet for the Pelorus River catchment displayed larger error in shape and peak, indicated by lower NSE values and larger PEPF values. While error in the model predictions may have been a result of errors in the model representation of physical processes in the catchment, a significant level of the error could be attributed to inaccurate rainfall input from the VCSN, which in turn may have been due to insufficient data from surrounding climate stations on which to base climate estimates. Conversely, the flood hydrographs generated by TopNet for the Ahuriri River displayed a lower level of error, which suggested that the model for the Ahuriri River catchment is more accurate than the model for the Pelorus River catchment. This may be due to a higher level of accuracy in the rainfall input from the VCSN, enabled by relatively high quality climate station data. Assuming TopNet models physical processes with a similar level of accuracy in both catchments, it could be concluded that the significant error in flow predictions in the Pelorus River catchment was mostly due to poor rainfall input from the VCSN.

The stochastic disaggregation of daily rainfall from the VCSN produced a random rainfall signal across the catchment that the TopNet model then used to predict the runoff hydrograph. The observed flow hydrograph, however, was the response to an actual rainfall event with a specific rainfall signal. It would be highly unlikely that the randomly generated rainfall signal would display a similar distribution to the actual rainfall event. As such, the error in the predicted flood hydrographs was expected since temporal distribution of rainfall was a significant factor in catchment response. The Ahuriri River catchment displays a rapid response to a rainfall event and has a small time of concentration (Caruso et al., 2013). The Pelorus River catchment was expected to behave similarly due to its steep topography. Rapid response to rainfall can amplify any temporal error in rainfall input. Hence, it was expected that model predictions made using a stochastic rainfall disaggregation displayed a high level of error in both the Ahuriri River catchment and the Pelorus River catchment.

Conversely, the station-based rainfall disaggregation generated a rainfall signal based on observed rainfall in or near the catchment. The daily rainfall provided by the VCSN was disaggregated into hourly rainfall following the distribution of the corresponding observed storm event. In the Ahuriri River catchment, station-based rainfall disaggregation was based on actual precipitation data from two points in the catchment – one near the headwaters, and one in the lower reaches (Figure 3-13). This allowed the TopNet model to develop a relatively accurate temporal and spatial rainfall distribution. Taking that into account, along with the rapid response of the Ahuriri River catchment to precipitation events, it was expected that the error was generally less when the model used daily rainfall disaggregated into an hourly rainfall input using station data than when using a stochastic hourly rainfall distribution. Station-based rainfall disaggregation appeared to be an improvement upon stochastic rainfall disaggregation when modelling events in the Ahuriri River catchment, although the error was still significant in the smallest high flow event prediction. This may have been a result of inaccurate total rainfall input, the model calibration, or the model's ability to approximate physical catchment processes.

The observed rainfall data used in the station-based disaggregation of daily rainfall in the Pelorus River catchment was derived from either two or three stations, depending on the time period of the simulation and completeness of the rainfall data series during that period, in the area surrounding the northeast end of the catchment (Figure 3-13). The stations were run by TDC and MDC and were, by their own admission, not a thoroughly reliable source of rainfall data. The stations were primarily for flood warning and were low priority assets, hence they received little funding and maintenance. Furthermore, the stations were located outside the catchment so may not have been subject to the same weather systems as the Pelorus River catchment itself. Hence, error in the rainfall distribution may have been significant and not an accurate representation of actual precipitation events in the catchment. This was likely the primary cause of the significant error in the modelled flood hydrographs on the Pelorus River. The error was such that the hydrographs predicted using daily rainfall disaggregation based on precipitation data from the stations surrounding the Pelorus River catchment appeared to offer no consistent improvement over hydrographs predicted using stochastic disaggregation of daily rainfall, possibly due to orographic effects and measurement error, as discussed.

The representation of the physical catchment characteristics in each model was also likely to influence the performance of the model. Assuming that the TopNet model is an accurate representation of the physical processes acting in the catchment, misrepresentation of the physical characteristics that influence such processes may be a source of error in the model. River bathymetry and bed topography and alignment can be critical elements of the model, especially when considering flow routing through the catchment. TopNet uses a one-dimensional Lagrangian kinematic wave routing scheme to model flow through the catchment. Although this is a common method of flow routing, and generally accepted as an appropriate method, it may have been responsible for some level of error typical of numerical approximations of physical phenomena. There has been little investigation into the channel characteristics of the Pelorus River and its tributary streams, so it was possible that parameters such as Manning's *n*, depth, and width, were approximate and not an accurate representation of the actual channel. This may have been a source of error in the model predictions for flood flows in the Pelorus River catchment. The Ahuriri River has been studied more intensively, so it was likely that the channel parameters in the model of the catchment were a more accurate representation of the actual scenario. However, some lengths of the Ahuriri River are braided and the channels are inclined to change significantly over a short period of time. Hence, the model may have responded to rainfall events using a more recent channel configuration, but the river may have displayed different channel properties at the time of the event. This may have resulted in errors in the hydrographs generated by the model when compared to the observed hydrographs. Conversely, during a high flow event the individual channels in a braided system are likely to overflow and the runoff will occupy the breadth of the riverbed. Hence, the channel bed topography and alignment may not have a strong influence on flood flows. It would, however, be more likely to influence low flow characteristics.

As a continuous model of water balance, the model predicted cumulative runoff discharge over a longer period with a high level of accuracy regardless of the method of rainfall input, although there was some improvement to the model when using precipitation station data for rainfall disaggregation in the Ahuriri River catchment model. The majority of maximum daily flows in each catchment were significantly less than the high flow events that have been modelled in this research project, and most of the discharge was low to average. This may indicate that the physical runoff mechanisms and hydrological characteristics of low and average flows were well-represented in TopNet, and that TopNet is suitable for long-term water balance modelling as intended. The accurate cumulative flow predictions over a longer period of three years also suggested that the calibration of each model was suitable for the initial purpose of the model, which was predicting water balance across the catchment with less focus on flood flows.

It appeared that, provided the observed rainfall data reflected the precipitation behaviour of the catchment with reasonable accuracy, using the data to disaggregate daily rainfall from the VCSN into an hourly hyetograph offered measurable benefits over the stochastic method of disaggregating daily rainfall. This was demonstrated in the model for the Ahuriri River catchment, where two rainfall stations located within the catchment contributed to the disaggregation of daily rainfall estimates, and the model flood predictions were significantly more accurate than the predictions made using stochastically disaggregated daily rainfall input to the model. Conversely, inaccurate station data may have a detrimental effect on the model predictions. The model predictions for the Pelorus River suggested that stochastic disaggregation of daily rainfall estimates may have been a better rainfall input. The station-based disaggregation of daily rainfall input to the model did not result in significantly higher levels of accuracy in the model when compared to stochastic rainfall disaggregation, and in fact caused a lower level of accuracy in some predictions for the Pelorus River catchment model.

Hence, station-based hourly disaggregation of daily rainfall was used for the remainder of this research project for modelling the Ahuriri River catchment, and stochastic rainfall disaggregation for the Pelorus River catchment model.

4.2 Modelling High Flow Events

Following the evaluation of the models for predicting flood events and subsequent discussion regarding the use of the two TopNet models in their current form for this research project, the models were used to simulate six additional flood events from the historical record. Adding to the three events used in the evaluation of each model, a total of nine high flow events was used to attempt to quantify the difference between model predictions and observed flows. Where the error in the model prediction was large, the observed rainfall and rainfall estimated by the VCSN were compared to determine whether the rainfall input was a likely cause.

4.2.1 High Flow Events on the Ahuriri River

The high flow events that were modelled and compared to the observed flows are shown in Table 3-4. The results are presented in Table 4-3 and Figure 4-17. Following the model evaluation, it was found that disaggregating daily rainfall estimated using observed data from nearby rainfall gauge stations improved the model prediction, provided the rainfall gauge stations were within the catchment boundaries and were spread throughout the catchment to allow spatial and temporal variability to be reasonable represented. The high flow events modelled in the Ahuriri River catchment used daily rainfall that was disaggregated into hourly rainfall based on precipitation gauge station data. The distribution of flood flows in the Ahuriri River was shown to be well-modelled by the GEV distribution (Figure 3-9) (Caruso et al., 2013), so the return period of high flow events were derived from the GEV distribution for use in this exercise. While Caruso et al. (2013) also recommended using the three parameter Lognormal distribution, the GEV and the Lognormal showed a near-identical fit up to the 100-year event. The observed flows were all below the magnitude of the 100-year flood so may be modelled equally well by the GEV alone.

There were three obvious outliers in the data set for peak flow for the modelled high flow events – the 1979 event, the 1995 event, and the 2000 event (Figure 4-17). If a modelled event with an ARI of greater than 10 years had a PEPF of greater than 10%, the prediction was considered an outlier. Similarly, if a modelled event with an ARI of less than 10 years had a PEPF of greater than 40%, the prediction was considered an outlier. The permitted error for smaller events was considerably larger because the flood risk from such events is considerably less, and so making accurate predictions for small events is less important. Following the comparison of the observed rainfall and the rainfall provided by the VCSN leading up to the high flow events, all three were discarded from the sample data set. The rainfall data for the December 1979 event appeared to be a daily average of the observed rainfall instead of hourly observations, and as such the station-based disaggregation of the daily rainfall estimate was based on the daily average of the observed rainfall data. This was likely a result of an older gauging station – newer data sets from a different gauging station were at an hourly time-step. The implication of this was that the rainfall data was provided as constant rainfall for each 24-hour period giving a hyetograph that was not an accurate reflection of the temporal variation that can be so important when modelling flood flows (Figure 4-19). Hence, the flow prediction from the December 1979 event was discarded from the analysis. This was also the case for the October 1978 event, which was also discarded as a result of the daily observed rainfall data (Figure 4-20).

While the observed rainfall hyetograph and the disaggregated VCSN hyetograph for the December 1995 high flow event displayed a similar shape (Figure 4-21), the total observed rainfall and total VCSN rainfall input differed significantly. The rainfall gauge stations measured 213mm of rainfall averaged between the two rainfall gauges, while the VCSN predicted 310mm – an overestimate of 46%. This was likely to be the main cause of the error in the model prediction for the peak flow, which was an over-prediction of peak flow by 32%, and hence the December 1995 event was discarded from further analysis. Like the December 1995 event, the rainfall input from the VCSN to the model for the December 2000 event displayed a similar hyetograph shape to the observed rainfall data (Figure 4-22). Furthermore, the total rainfall predicted by the VCSN was 134mm, compared to the total observed rainfall of 136mm – a difference of 1%. Hence, the December 2000 event was not discarded and the error may not have been a result of poor rainfall input.

With the data points that displayed error and were shown to have erroneous rainfall input removed from any further analysis, it was apparent that the TopNet model for the Ahuriri River catchment under-predicted small flood flows but had a high level of accuracy when predicting larger flows (Figure 4-17, Figure 4-18). The three smallest events considered, all with an AEP less than 0.2, were significantly underestimated and had an average PEPF of −43.7%. The three large events in the study, disregarding the three outlying events, were all predicted with a high level of accuracy and had an average PEPF of −2.4%.

Table 4-3: Results for the flood events modelled in the Ahuriri River catchment

Event	ARI	PEPF	Comments
9 Jan 1994	41 years	2.0%	No need to compare rainfall input with observed hyetograph.
21 Dec 1984	33 years	−2.3%	No need to compare rainfall input with observed hyetograph.
3 Dec 1979	28 years	−48%	Large error, rainfall input was compared to observed hyetograph. Event discarded due to observed rainfall recorded at daily instead of hourly timestep.
13 Dec 1995	26 years	32%	Large error, rainfall input was compared to observed hyetograph. Event discarded due to poor rainfall estimate from VCSN.
14 Oct 1978	7.9 years	−28%	Event discarded due to observed rainfall recorded at daily instead of hourly timestep.
16 Nov 1999	7.4 years	-3.0%	No need to compare rainfall input with observed hyetograph
19 Sep 2002	3.7 years	−29%	Large error but small event so rainfall not investigated
28 Dec 2000	3.4 years	−66%	Large error but upon further investigation rainfall error was negligible so event was not discarded.
30 Mar 1987	2.8 years	-36%	Large error but small event so rainfall not investigated

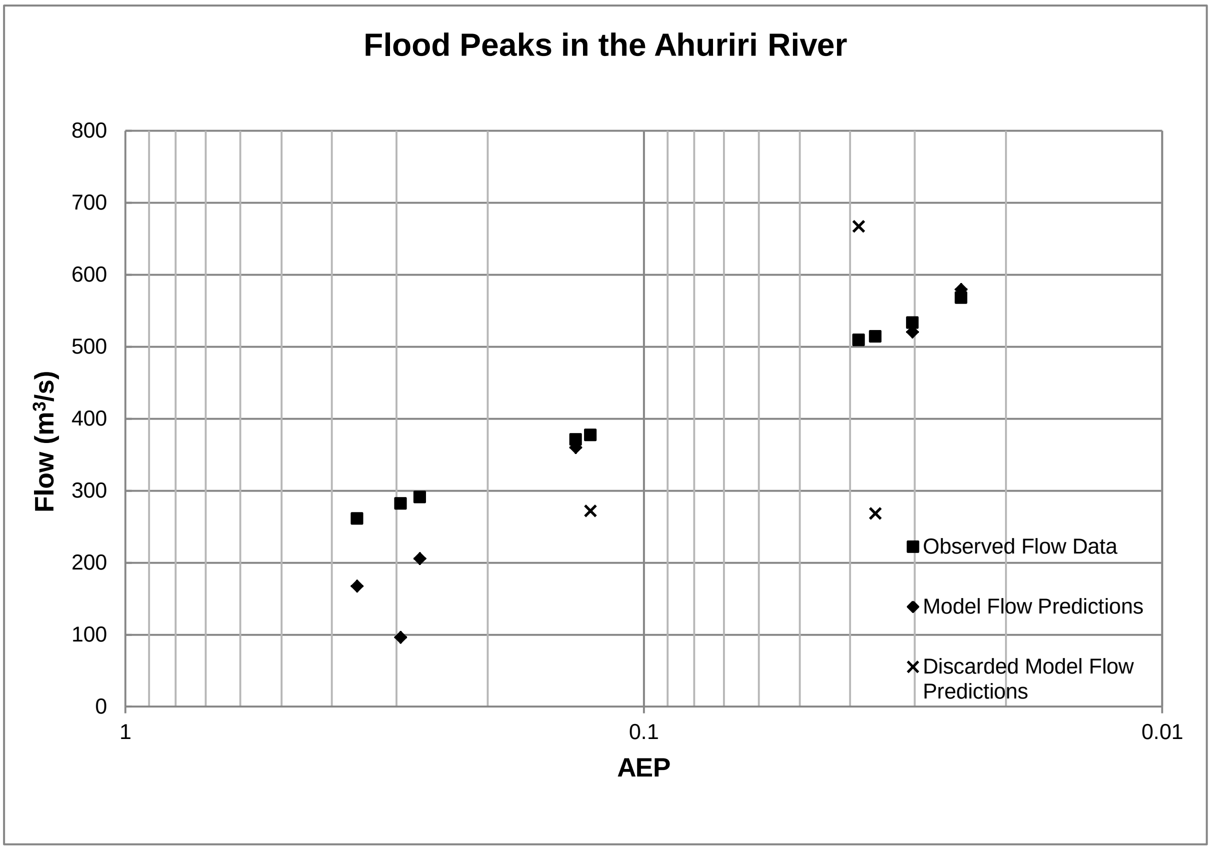


Figure 4-17: Observed and modelled flood peaks on the Ahuriri River.

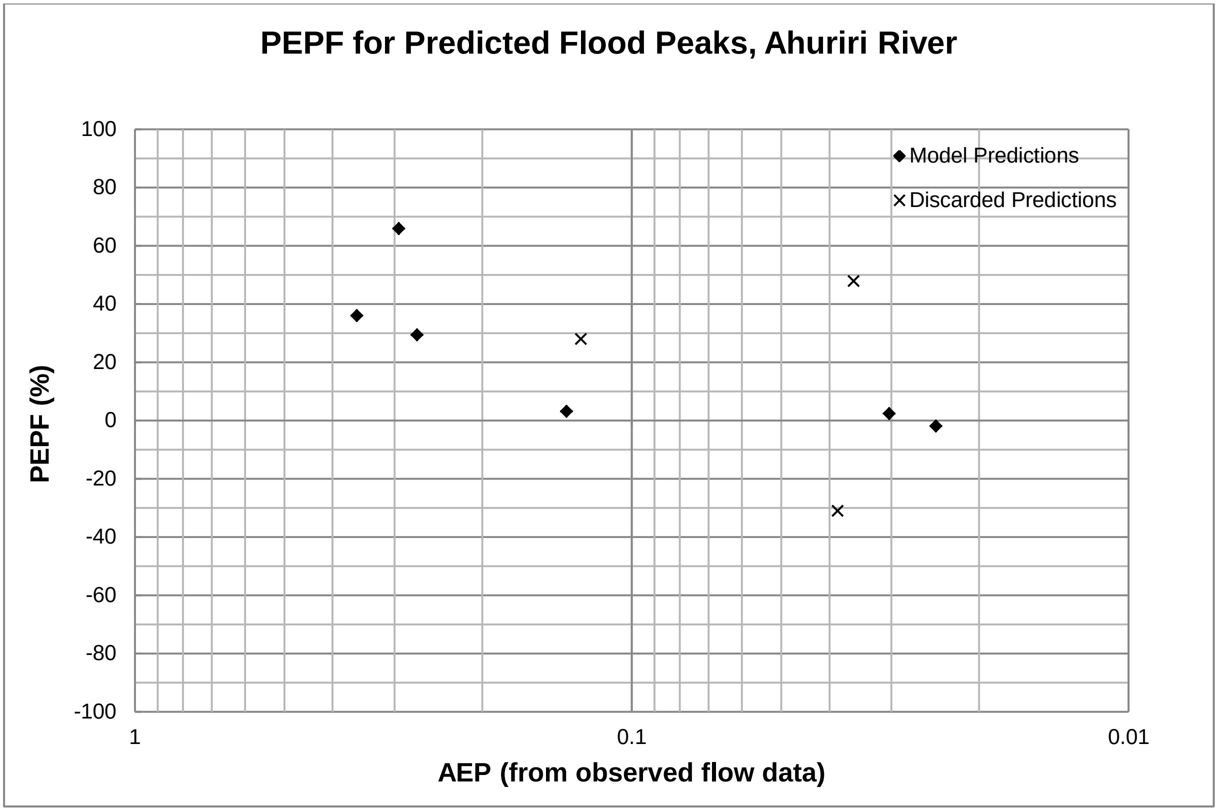


Figure 4-18: PEPF of observed peak flow and predicted peak flow, Ahuriri River

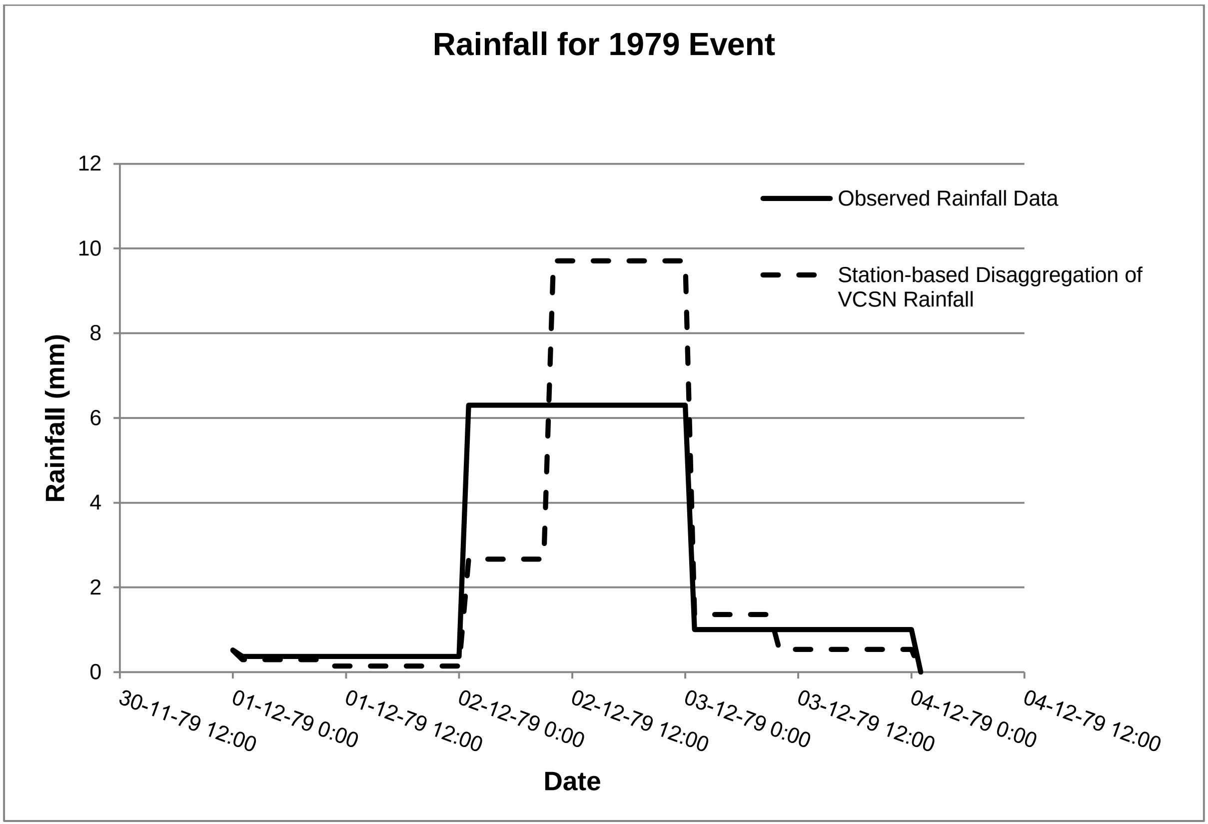


Figure 4-19: Observed rainfall and rainfall estimated from VCSN for the December 1979 event

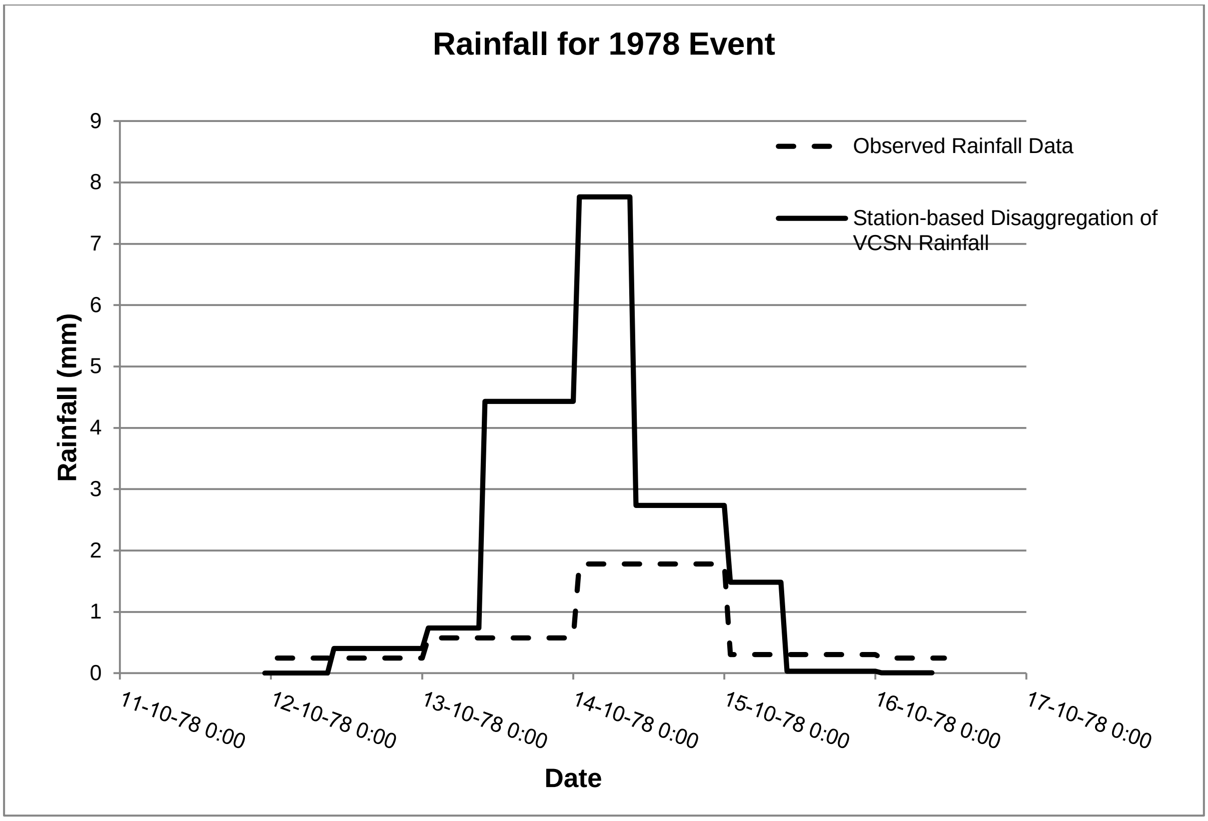


Figure 4-20: Observed rainfall and rainfall estimated from VCSN for the October 1978 event

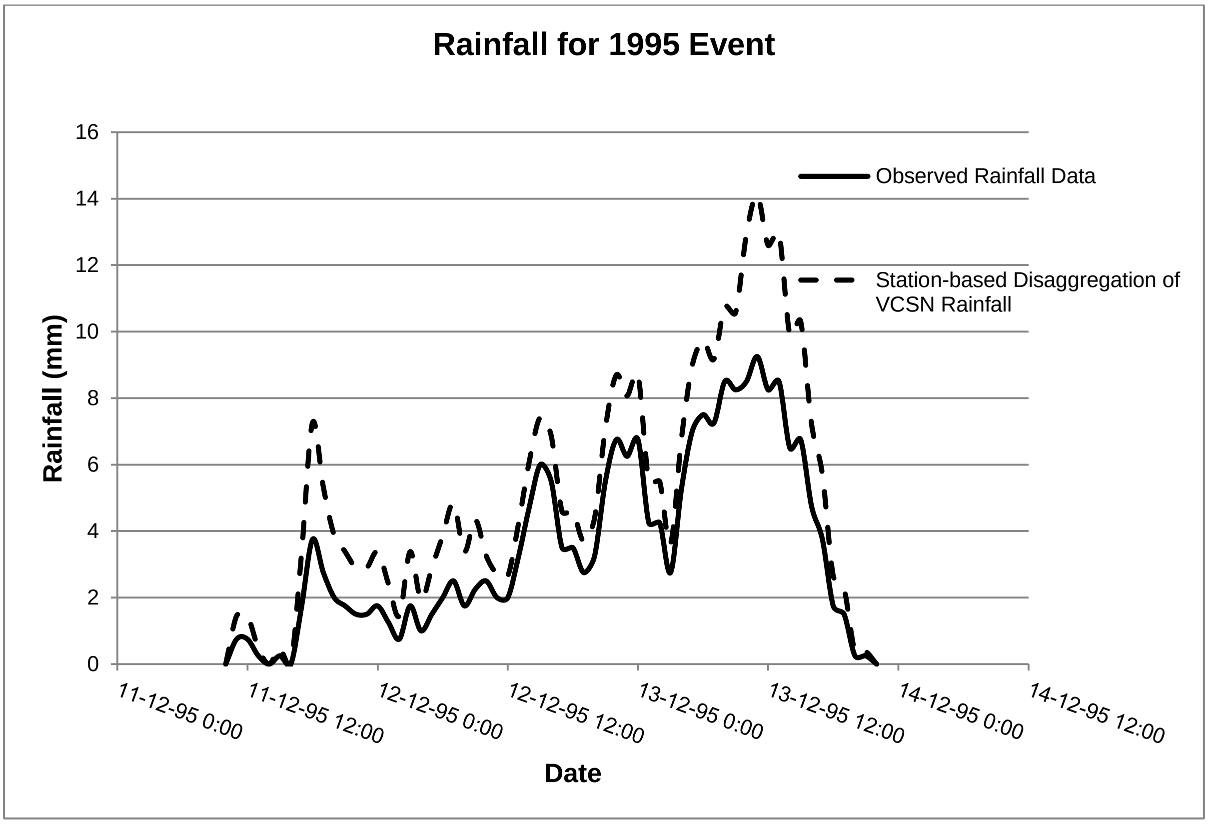


Figure 4-21: Observed rainfall and rainfall estimated from VCSN for the December 1995 event

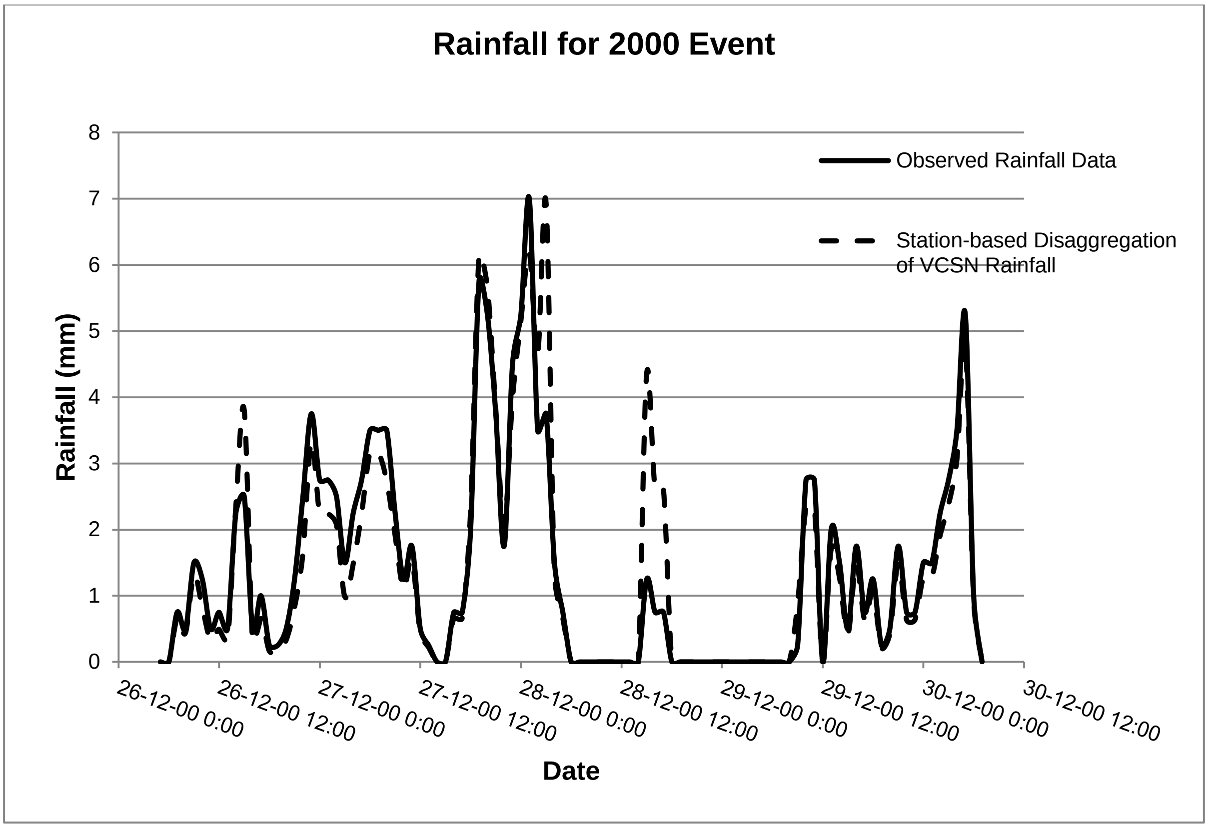


Figure 4-22: Observed rainfall and rainfall estimated from VCSN for the December 2000 event

4.2.2 High Flow Events on the Pelorus River

The high flow events on the Pelorus River that were modelled and compared to the observed flows are shown in Table 3-4. Little benefit was apparent when the model disaggregated daily rainfall estimates using observed precipitation station data instead of stochastically. Hence, flood events on the Pelorus River were modelled using stochastic disaggregation of daily rainfall estimates from the VCSN. Like many New Zealand rivers, observed flood peaks on the Pelorus River appeared to be well-predicted by the GEV distribution (Figure 3-10), hence the AEP for the flows modelled in this exercise were taken from the GEV distribution that was fitted to the observed flood peak data. It has been discussed that the rainfall input to the model for the Pelorus River catchment is likely to be unreliable. As such, it was assumed that the rainfall input was consistently poor so no comparison of observed and estimated rainfall input for outlying data points was conducted. Despite this, identifying how strongly the model predicts larger and smaller flows may be useful when modelling land use change scenarios in the Pelorus River catchment.

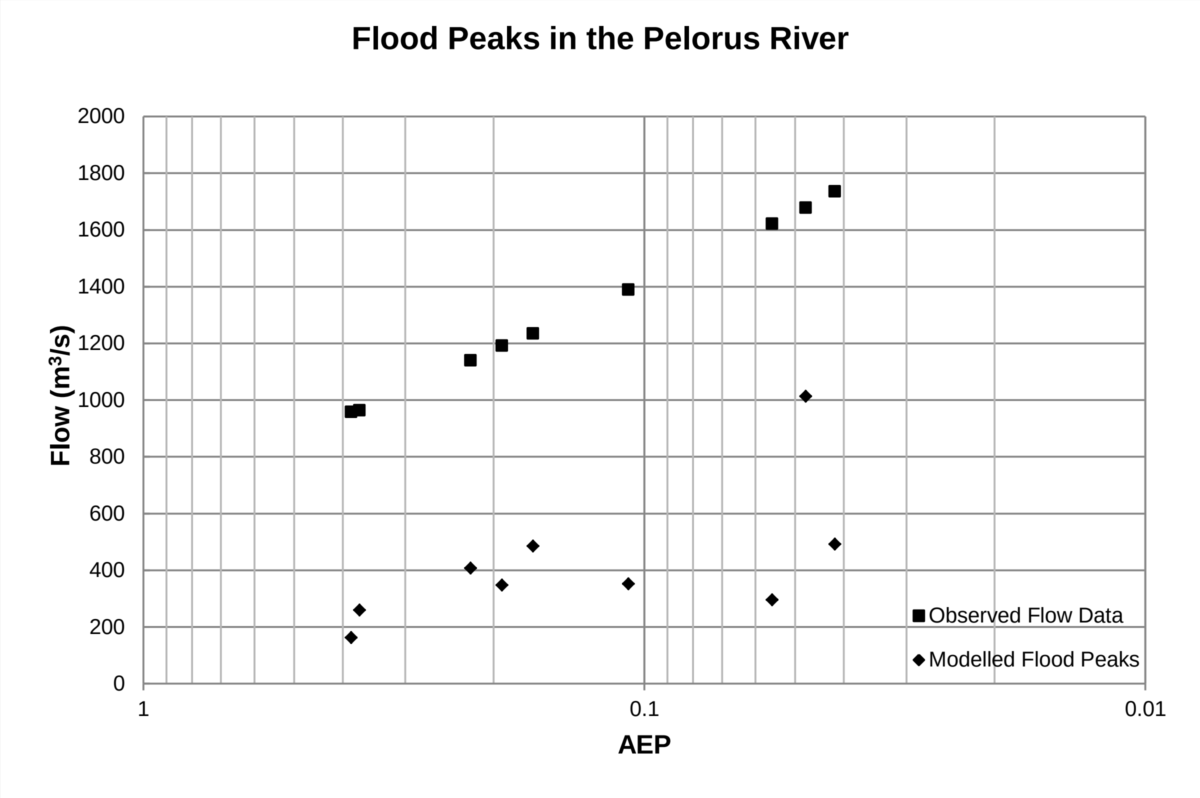


Figure 4-23: Observed and modelled flood peaks in the Pelorus River

There was a consistently significant difference between the observed flow peaks and the modelled flow peaks for all events modelled in the Pelorus River catchment. The model tended to significantly underestimate the peak flow for each event (Table 4-4). The average PEPF was −69% with a standard deviation of 13%. PEPF is also presented in Figure 4-24, where it was clear that the difference was large for every modelled flow and did not appear to be influenced by the magnitude of each event. As discussed, the large error may be a result of inaccurate rainfall input. Following the modelling and discussion of high flow events, the Pelorus River catchment model was not discarded, but the error was taken into account.

Table 4-4: Results for the flood events modelled in the Pelorus River catchment

Event	ARI	PEPF	Comments
21 Oct 1983	24 years	−72%	The potential for poor rainfall input to the Pelorus River catchment model was discussed and assumed to be a significant cause of error in the model predictions for all events. Hence, no further investigation into rainfall input was conducted.
1 July 1998	21 years	−40%	
23 Feb 1995	18 years	−82%	
30 Jan 2000	9.3 years	−75%	
23 July 1988	6.0 years	−61%	
25 Jan 1986	5.2 years	−71%	
13 June 1993	4.5 years	−64%	
24 Jan 1991	2.7 years	−73%	
21 Apr 1987	2.6 years	−83%	

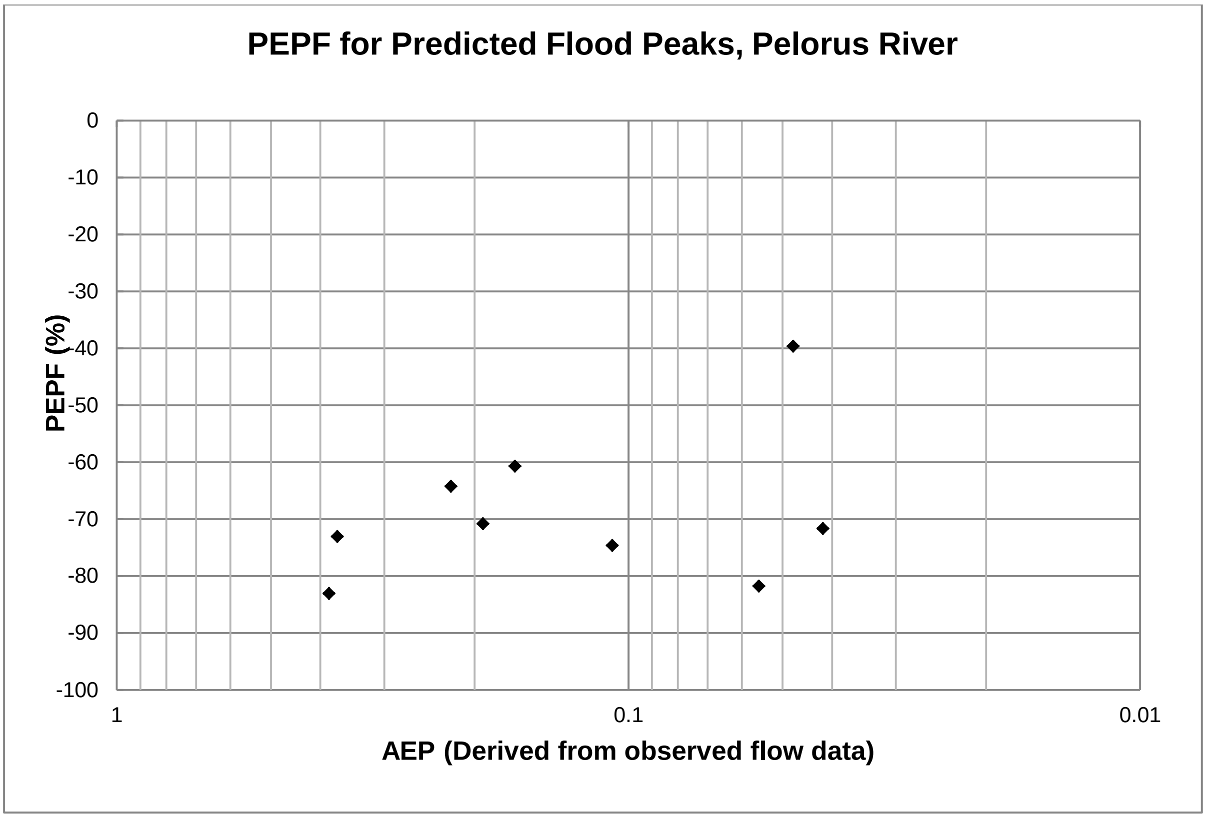


Figure 4-24: PEPF of observed and predicted flood peaks, Pelorus River

4.2.3 Discussion of Modelling High Flow Events

While it has generally been acknowledged that TopNet is a suitable long-run water balance hydrologic model, it may be useful to use the model for flood prediction in New Zealand catchments, especially given TopNet models have been developed for a number of catchments by NIWA. Furthermore, the model has been generally untested in mountainous catchments. Hence, the TopNet models for the mountainous catchments of the Ahuriri River and the Pelorus River, developed by NIWA as a long-run water balance model, were tested against observed flood flows in an attempt to evaluate their ability to predict a range of historic flood events. It was hoped that a trend between the model predictions and the observed flood flows could be identified and carried forward in the research project.

Given the established relationship between the quality of rainfall input to a hydrologic model and the accuracy of the flow predictions, it was not surprising that the error in the model predictions for the Ahuriri River was large when the rainfall input was found to be erroneous. This occurred for three events that were consequently discarded from use in the development of a relationship between model predictions and observed flow events. The rainfall station gauges provided daily rainfall data for the two oldest events in 1978 and 1979. This resulted in poor disaggregation of the VCSN rainfall estimate based on station data and hence the error in the flow predictions was large. Fortunately, this appeared to only affect the two oldest events and more recent rainfall data was recorded at an hourly timestep. Of the remaining two events that warranted further investigation into rainfall input to the model, only the December 1995 event displayed significant error in the VCSN estimate of total rainfall volume. The December 2000 event displayed a larger PEPF but an insignificant rainfall error.

After proceeding with the analysis of the modelled flows, with the exception of the three discarded events from October 1978, December 1979, and December 1995, it appeared that the model predicted larger events with a significantly higher level of accuracy than smaller events. The three events with an ARI greater than 5 years displayed an average PEPF of 2.4%. By comparison, the remaining three events with ARI less than 5 years displayed an average PEPF of 44%. This suggests that, provided the rainfall input from the VCSN corresponded well to actual rainfall, the TopNet model developed for the Ahuriri River catchment was better able to predict larger events than smaller events. From an engineering and planning standpoint, this may significantly increase the usefulness of the TopNet model for assessing flood flows in mountainous catchments, as larger flows are generally of greater concern. However, where error was small, rainfall input was not investigated. Instead, it was assumed to be reasonably accurate. While unlikely, it is possible that error in rainfall input was counteracted by error in the model approximation of catchment processes, resulting in a small level of error in the simulation of larger events. Further investigation into sources of error in the model may be recommended in future.

As expected from the results of the initial model testing, the peak flow predictions on the Pelorus River continued to display significant PEPF. The model consistently under-predicted the peak flow and the magnitude of error seemed independent of the magnitude of the observed flow event. There was no rainfall gauge station within the Pelorus River catchment, and the surrounding gauges have been acknowledged by their operators to be unreliable. Hence, further investigation into rainfall input as a potential source of error to the model was not conducted. However, given the sparse network of climate stations contributing to the VCSN in the upper South Island, particularly in alpine areas such as the upper reaches of the Pelorus River catchment, it may be appropriate to assume a considerable level of error in the rainfall input to the model. Hence, a significant level of error in the model predictions may be attributed to error in the rainfall input. Nevertheless, error also may have been a result of poor approximation of the physical processes acting in the specific catchment. The model for the

Ahuriri River catchment appeared to well-approximate such processes, which was evident by a high level of accuracy when predicting peak flood flow provided rainfall input was also accurate. However, a similar ability to approximate catchment processes cannot be assumed for the Pelorus River catchment model due to potentially inaccurate rainfall input, and so must be taken into account. Further research into the efficiency and accuracy of the numerical approximations of catchment processes in TopNet was beyond the scope of this research project, but could be recommended for future research. Instead, the focus of this project was directed to the existing models and their ability to model flood flows in their current form.

In general, the flow predictions for the Ahuriri River were conservative, in that the model underestimated peak flood flows. The flow predictions for the Pelorus River were always significantly conservative. The application of TopNet to the DMIP also found that the model tended toward conservative predictions of runoff (Bandaragoda et al., 2004), however the catchments modelled in the DMIP were not mountainous and displayed different hydrological characteristics to the Ahuriri and Pelorus River catchments.

Another finding of the DMIP was that TopNet performed better in smaller catchments than in larger catchments (Reed et al., 2004). This suggested that the process of runoff generation in TopNet well-approximated the physical catchment processes, but that the channel routing component may be less robust. Both the Ahuriri and Pelorus River catchments, measuring 580 km^2 and 380 km^2 in area, respectively, are considered small catchments when compared to the catchments used in the DMIP. The model showed the ability to predict flood flows with a high level of accuracy in the Ahuriri River catchment, where the rainfall input to the model correlated well with the observed rainfall. This suggested that TopNet was indeed well-suited to modelling runoff in relatively small catchments, and that it also appears to be a useful modelling tool in mountainous catchments. The model would rely more heavily on channel routing in a larger mountainous catchment, and before any conclusions can be drawn regarding the suitability of the model to predict flood flows in such catchments further testing would be recommended.

In semi-arid mountainous catchments such as the Ahuriri River catchment, the model predicted model flood flow reasonably well. Larger flood flows were to be modelled with a greater accuracy than smaller flood flows. This may be a limitation of the model if applied to a floodplain management scenario intended to model annual floods, but the model is more likely to be a useful tool in predicting large floods that may pose a risk to infrastructure and population. In forested mountainous catchments, such as the Pelorus River catchment, the TopNet model appeared to be less reliable and underestimated flood flows by a significant magnitude. However, this may have been a result of poor rainfall input and not necessarily a reflection of the ability of the model to approximate the physical processes acting in the catchments. To further assess the usefulness of the model for predicting flood flows under current catchment conditions, the model may be tested in a number of other mountainous catchments in areas where the rainfall estimate from the VCSN is likely to be more accurate, or using a different method of rainfall input to the model.

4.3 Modelling Future Land Use Scenarios

A key output of this research investigation was an assessment of the effects of land use change on the flood hydrology of steep catchments using the TopNet model. The model for each catchment was modified to reflect potential future land use scenarios. In total, four scenarios were developed for each catchment – two different land use changes each with two different extents.

4.3.1 Future Scenarios in the Ahuriri River Catchment

It has been shown that, provided the rainfall input from the VCSN is an accurate estimate of actual rainfall, the TopNet model for the Ahuriri River catchment can accurately predict flood peaks. There was a higher level of accuracy in the prediction of larger flows than smaller flows. While the October 1978, December 1979, and December 1995 events were discarded from the previous analysis, they were reinstated for this section of the investigation. The three events were discarded because they had poor rainfall input from the VCSN. This may have been the cause of significant error when comparing the predicted flows to the observed flows, but the rainfall input should not influence the ability of the model to predict the change in peak flow as a result of land use change.

Details of the land use change scenarios modelled in the Ahuriri River catchment are presented in Table 3-8 and Figure 3-15. The summarised results of the simulations are presented in Table 4-5. The peak flow for each flood event and each scenario is shown in Figure 4-25 and the change in peak flow is shown in Figure 4-26. A detailed table of results and the hydrographs for each scenario and event are included in Appendix I.

Table 4-5: Average results of the land use change scenarios modelled in the Ahuriri River catchment

Future scenario in the Ahuriri River catchment	Average difference in peak flow (%)	Average difference in time to peak
Conversion to pasture over 22%	0.7%	0.1 hours
Conversion to pasture over 40%	2.6%	0.1 hours
Native reforestation over 22%	−0.9%	0.0 hours
Native reforestation over 40%	−1.8%	0.3 hours

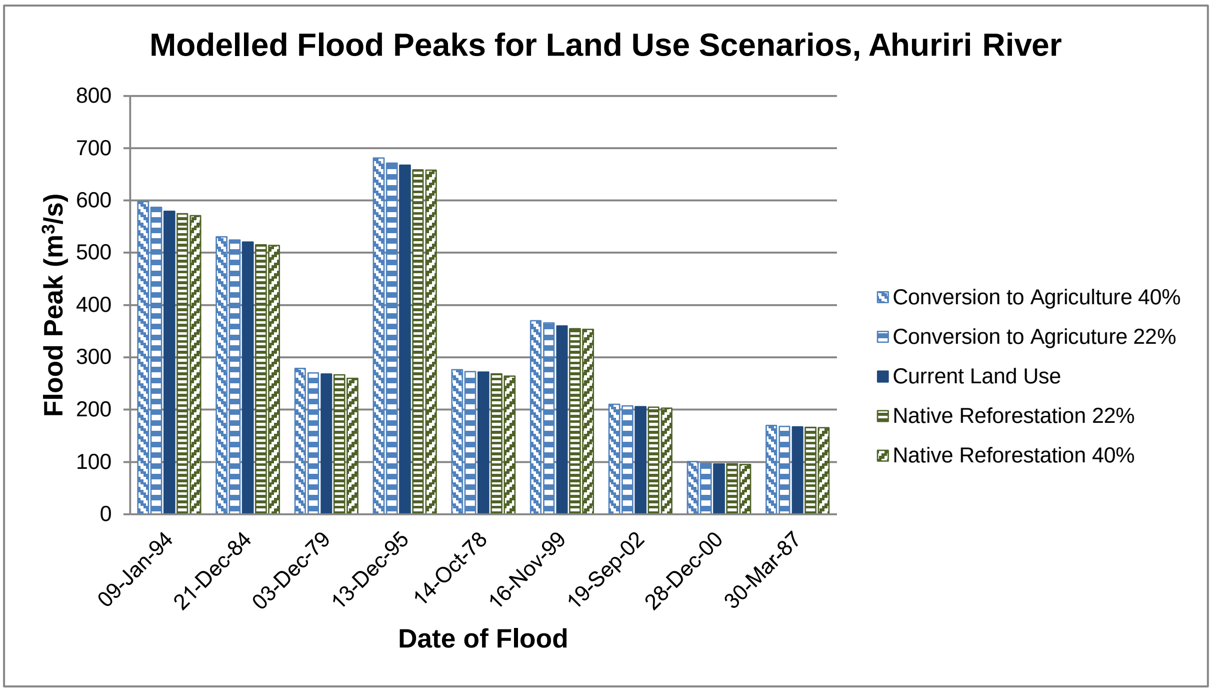


Figure 4-25: Modelled flood peaks for land use scenarios in the Ahuriri River catchment

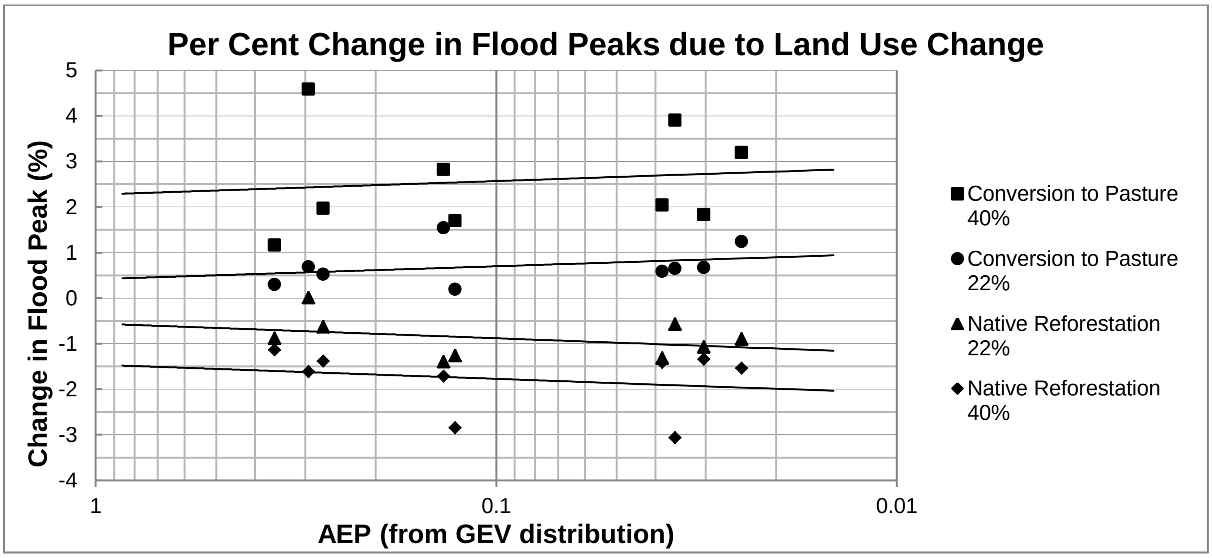


Figure 4-26: Per cent change in peak flow as a result of land use change for high flow events modelled in the Ahuriri River catchment

Note: The logarithmic trend lines in Figure 4-26 indicate that, in general, the magnitude of the per cent change in flood peak increases with the size of the flood event. However, the trend is small and may fall within the margin of error of the TopNet model.

The average increase in peak flow magnitude on the Ahuriri River due to the conversion of mostly unmanaged land to pasture or agricultural land use over 22% and 40% of the catchment was found to be 0.7% and 2.6%, respectively (Table 4-5). The reforestation of 22% and 40% of the catchment resulted in a decrease in flood peaks of 0.9% and 1.8%, respectively, on average (Table 4-5). It is clear that none of the scenarios produced a significant change in flood peak (Figure 4-25). After plotting the per cent change in peak flow due to land use change against the AEP of the corresponding observed event under the original catchment conditions, it appeared that larger events experienced a greater per cent change in peak flow due to land use change than smaller events (Figure 4-26). Following the trend lines in Figure 4-26, the increase in flood peak was 0.25% greater for a 50-year flood than for a 10-year flood due to the conversion of tussock grassland to pasture. Similarly, the decrease in flood peak for a 50-year event was 0.25% greater than the decrease in flood peak for a 10-year event as a result of reforestation in the catchment. However, given the inherent level of error present in all hydrologic models and the small sample size of 9 events, and the very small increase in change in flood peak shown in Figure 4-26, this trend may not be valid.

The simple sensitivity analysis of K_S using the conversion of tussock grassland to pasture over 40% of the Ahuriri River catchment showed that leaving K_S unchanged from the original, unmodified values for each subcatchment in the model resulted in an average increase in peak flood flow of 1.4% over the nine floods modelled, which was attributed to the effect of modifying only the canopy storage capacity and the canopy evaporation enhancement factor in the model to reflect land use change to pasture. Increasing K_S by 100% from the original, unmodified conditions across 40% of the catchment resulted in an average increase in peak flow of 2.6% for the nine flood events. Increasing K_S by 200% resulted in an average increase in flood magnitude of 3.2% (Table 4-6, Figure 4-27).

Table 4-6: Average change in peak flood flow due to different K_S across 40% of the Ahuriri River catchment

Change in Hydraulic Conductivity K_S	Average Change in Peak Flood Flow
No change from original model	1.4%
100% increase from original model	2.6%
200% increase from original model	3.2%

Note: Canopy evaporation enhancement factor and canopy storage capacity were modified to reflect land use change from tussock to pasture across 40% of Ahuriri River catchment and were not changed for each K_S.

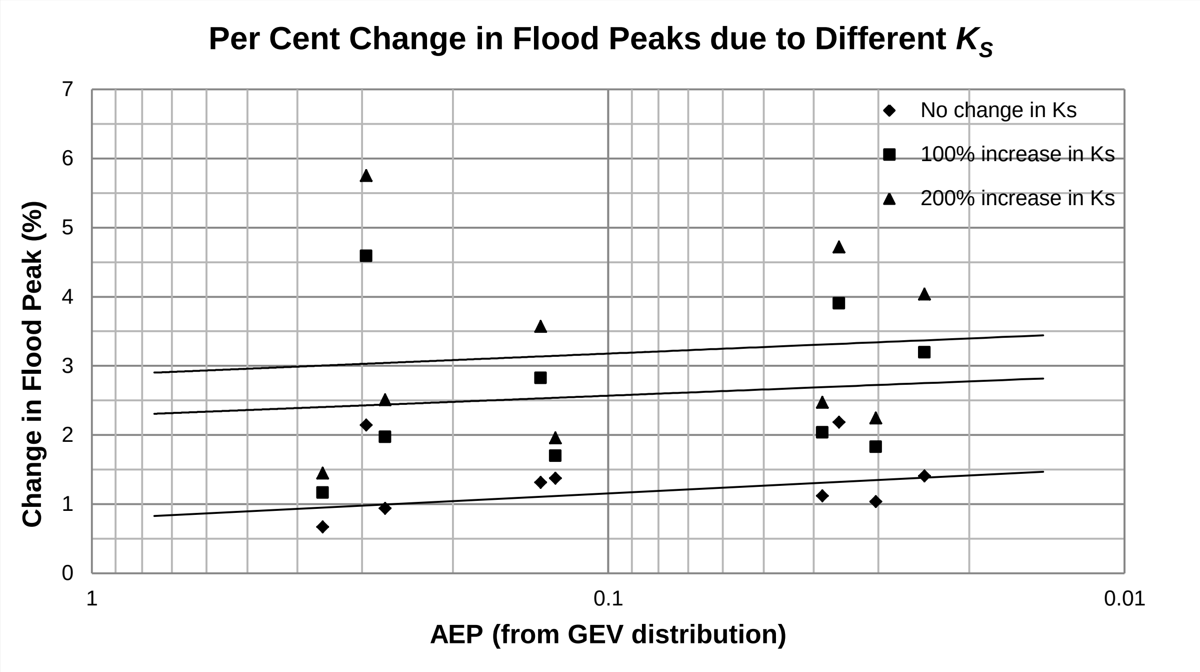


Figure 4-27: Per cent change in flood peaks due to different K_S values across 40% of the Ahuriri River catchment

Note: The trend lines in Figure 4-27 suggest that the effect of different values of K_S on the per cent change in flood peak is approximately constant and independent of flood magnitude or AEP for the range of flood magnitudes modelled. As with earlier results, the margin of error is sufficient so that the apparent increase in change in flood peak as AEP decreases may not be a valid trend.

4.3.2 Future Scenarios in the Pelorus River Catchment

It has been shown that the error in the peak flow predictions is significant for the Pelorus River catchment model. Although this may discount the TopNet model from being a useful tool in flood forecasting in the Pelorus River catchment in its current form, it may prove useful in attempting to quantify the effect of land use change on the flood hydrology of the Pelorus River catchment. The land use change scenarios developed and modelled in the catchment are described in Table 3-8, Figure 3-16, and Figure 3-17. A summary of the results of the simulations are presented in Table 4-7. The flood peaks and change in flood peaks predicted by the model are presented in Figure 4-28 and Figure 4-29, respectively. A detailed table of results and the hydrographs of the simulated flood flow in the unmodified catchment and the catchment under potential future land use are in Appendix I.

Table 4-7: Average results of the land use change scenarios modelled in the Pelorus River catchment

Future scenario in the Pelorus River catchment	Average difference in peak flow (%)	Average difference in time to peak
Conversion to pasture over 23%	0.5%	0.0 hours
Conversion to pasture over 42%	0.8%	0.0 hours
Forestry harvest over 14%	0.3%	0.0 hours
Forestry harvest over 28%	0.2%	0.1 hours

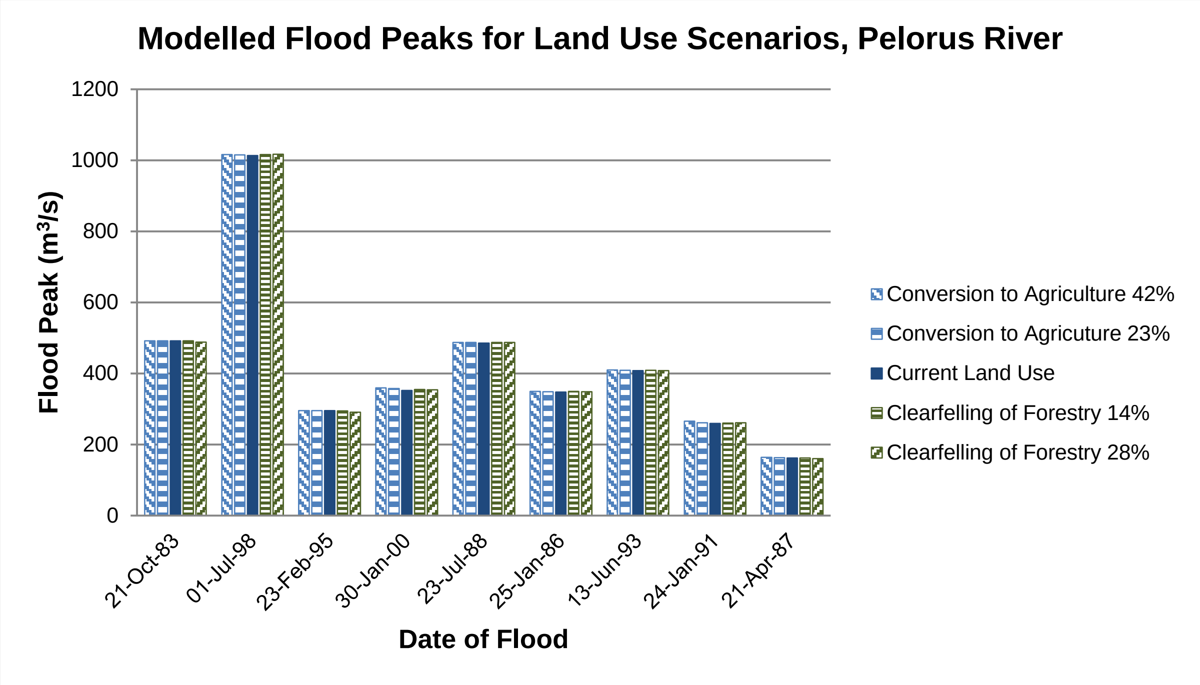


Figure 4-28: Modelled flood peaks for land use scenarios in the Pelorus River catchment

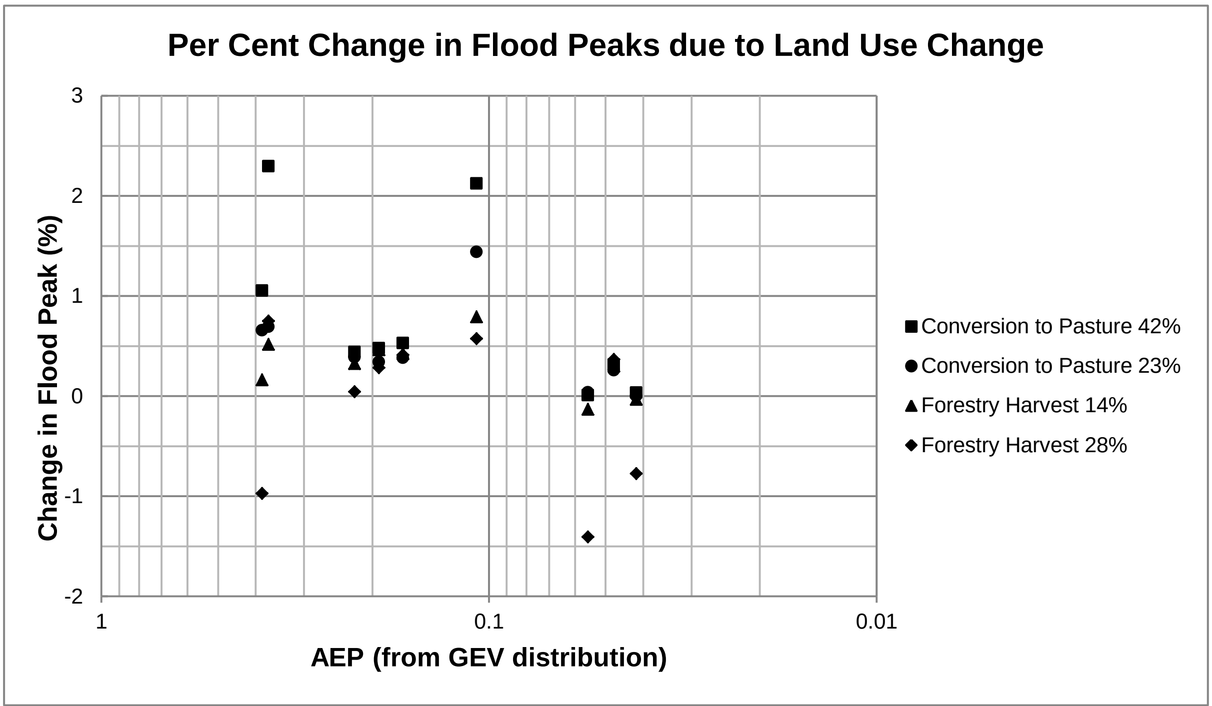


Figure 4-29: Per cent change in peak flow as a result of land use change for high flow events modelled in the Pelorus River catchment

The TopNet model predicted that all four land use scenarios would have a very small effect on the peak flood flow for the nine rainfall events modelled. The model predicted that peak flow would increase by an average of 0.5% and 0.8% if 23% and 42% of the Pelorus River catchment were converted to pasture, respectively. If clearfelling of forest were to occur over 14% and 28% of the catchment, the model predicted that peak flow would increase by an average of 0.3% and 0.2%, respectively. Figure 4-28 shows no significant change in flood peaks due to the land use change for any of the nine floods modelled. The per cent change in flow peak displayed no discernible trend in relation to the magnitude or AEP of the flows modelled for each land use scenario (Figure 4-29). The estimated difference in time to peak flow between the unmodified catchment and the potential future scenarios was negligible.

4.3.3 Discussion of the Effects of Future Land Use Scenarios

It is unlikely that the Ahuriri River catchment or the Pelorus River catchment will undergo land use change similar to the scenarios that were modelled in this research project. A significant area of each catchment is conservation land – the Ahuriri Conservation Park in the Ahuriri River catchment and the Mt. Richmond Forest Park in the Pelorus River catchment. However, there are numerous catchments with similar hydrological and topographical characteristics that do not have such protection. Findings from an attempt to quantify the influence of such land use changes on the Ahuriri and the Pelorus River catchments may be applied to similar catchments, and may prove a useful tool for assessing potential land use change in a resource management context.

While the peak flow predictions for each catchment were poor at times, especially for the smaller flood flows on the Ahuriri River and for all flows predicted on the Pelorus River, the model may still be able to be used to predict the effects of land use change on the flood hydrology of each catchment. Provided the TopNet model accurately approximated physical catchment processes, the difference in flow between the modified and unmodified catchment could be attributed to the land use change, given the rainfall input did not change between subsequent model runs of the same time period. Hence, the effect of land use change on flood characteristics predicted by the TopNet models for each catchment may be applied to the actual flow regime of each river, and similar river catchments, regardless of error in the model simulations.

Each of the TopNet models was modified for each catchment by changing the parameter multiplier to three key model parameters identified in a report for Environment Waikato: the saturated hydraulic conductivity of the soil K_S, the canopy storage capacity, and the canopy enhancement factor (Woods et al., 2009). This was considered the most appropriate method of simulating land use change in each catchment, which allowed different land uses to be simulated with relative simplicity. The chosen method for modifying the models did not change the spatial input files that form the basis for the physical representation of the catchment, but the less complex method of applying parameter multipliers was intended to have a similar effect. However, further research into this topic may benefit from modifying the physical representation of the land cover in the TopNet models, rather than modifying the calibrated parameters in the model to reflect land use change. Furthermore, the effects land cover and vegetation can have on runoff processes such as evapotranspiration, infiltration, and surface roughness and overland flow are not explicitly included as parameters in the TopNet model that can be used for calibration. Such processes may have an effect on runoff generation, and could affect the results of the model predictions.

Simulating the conversion of 22% and 40% of the land in the Ahuriri River catchment to agricultural or pastoral land resulted in an average increase in the predicted peak flow of 0.7% and 2.6%, respectively. There appeared to be no strong relationship between the magnitude of the predicted increase in peak flow and the magnitude of the peak flood flow, but a larger flood had a slightly larger increase in peak flow due to agricultural or pastoral land conversion, to the extent that a 50-year return period event may expect an increase in peak flow of 0.25% more than for a 10-year return period event (Figure 4-26). Given the established hydrologic characteristics of tussock and managed pasture, it was expected that the model predicted flood flows would increase. Tussock generally has a slightly lower canopy storage capacity, primarily due to a lower foliage density than pasture grasses, but this is more than compensated for by a significantly lower K_S, resulting in less runoff generation. The conversion of tussock grassland to managed pasture has not been extensively studied, particularly in mountain catchments and has been a relatively recent phenomenon in the high country of New Zealand. The majority of research done on tussock catchments in New Zealand has been in the Glendhu Catchments, Otago, which has considered the afforestation of tussock grassland. However, given the similarity in hydrologic properties between tussock and pasture, it was to be expected that the model may have predicted a relatively small increase in peak flow due to land use change. It was also noted that a small area of the Ahuriri River catchment upstream of the South Diadem river gauge was under agricultural use for the current scenario (Figure 3-3). While the area of current agricultural land use was not significant, it was likely that it reduced the impact of the potential future scenario.

The model was modified to reflect a change from tussock to pasture that was not irrigated, although irrigated pasture has become more widespread in the Waitaki Basin in recent years (Addison, 2009; Aqualinc, 2008). A number of studies have suggested that hydrological properties such as canopy storage capacity, which was modified to reflect land use change, does not change between irrigated and dry pasture (Rowe et al., 2002). Furthermore, saturated hydraulic conductivity K_S is likely to have a significant influence on flood peaks in the TopNet model (Woods et al., 2009). Irrigation of pasture using water abstracted from subsurface aquifers near São Paulo, Brazil, was shown to reduce the K_S of the soil significantly. This was attributed to high concentrations of sodium in the water causing soil damage, a decrease in soil macroporosity, and an increase in fine microporosity (Gonçalves et al., 2007). K_S of soil under irrigation can display significant temporal variation, depending on the maturity of the pasture root system, wetting and drying cycles, and biological activity (Mubarak et al., 2009). Hence, further investigation in to the soil properties of the Ahuriri River catchment is recommended before modelling the impact of the conversion tussock grassland to irrigated agriculture in the basin.

Conversely, simulating the reforestation of 22% and 40% of the land in the Ahuriri River catchment with native forest resulted in decrease in the predicted peak flow of 0.9% and 1.8%, respectively. As with the conversion to pasture, there appeared to be no strong relationship between the magnitude of the predicted increase in peak flow and the magnitude of the peak flood flow, although it appeared that a larger flow event would have a slightly larger decrease in peak flow due to reforestation in the catchment (Figure 4-26). Native forest displays a significantly higher canopy capacity than tussock grassland, the main land cover in the Ahuriri River catchment, which would result in less precipitation reaching the catchment floor. Forested land also displays a significantly higher K_S than tussock grassland, which would suggest a greater runoff generation, but the canopy capacity of the forest restricted the volume of runoff available for transport, resulting in a decrease in peak flow. Hence the reduction in peak flow was expected, but it may have been reasonable to expect the reduction to be more significant.

The primary resources for information regarding the conversion of tussock grassland to forest in New Zealand have been studies from the Glendhu Experimental Catchments, Otago. The Glendhu Experimental Catchments are two adjacent catchments, each with similar topography and climate characteristics. The GH1 catchment, with an area of 2.2 km^2, was the control catchment and was left with near-original tussock land cover. The GH2 catchment, with an area of 3.1 km^2, was planted with radiata pine across 67% of the catchment. It was found that afforestation of radiata pine, which has been shown to have similar hydrological properties to native forest, caused a 24.4% reduction in the 20-year flood and a 21.8%

reduction in the 2-year flood (Zhao, Xu, & Zhang, 2012). Furthermore, the reduction in peak flow due to afforestation was “relatively constant, except [for] extremely high and low flows” (Zhao, Xu, & Zhang, 2012, p. 1571). Similar results from the Glendhu catchments were observed by Fahey and Jackson (1997). These results from the Glendhu experiment agreed with the output from the TopNet model that suggested flood flow is reduced under afforestation of tussock grassland. However the Glendhu findings suggested a more significant reduction in flow would be observed. It should be noted that the GH2 catchment was afforested over 68% of its area, compared to the simulated change in the Ahuriri River catchment of 20.4% and 40.0%. It should also be noted that the Ahuriri River catchment, while still considered a small catchment with an area of 580 km^2, is significantly larger than the Glendhu catchments. The Ahuriri River catchment is also steeper and more mountainous, and is located in an alpine environment. These factors may influence the hydrology of the catchment and make it less sensitive to land use change.

The model predictions for the high flow events in the Pelorus River catchment were inaccurate. The model under-predicted peak flows in the river by an average of 69%. However, as discussed, this may not have invalidated any predictions regarding the effect of land use change on the flood hydrology of the Pelorus River catchment. The harvest and clearfelling of exotic forestry has typically occured over a smaller area than other land use changes such as pastoralism or reforestation, hence the model was modified to reflect clearfelling across 14% and 28% of the Pelorus River catchment, focussed in the lower reaches of the catchment regarded most suitable for forestry operations under the land use capability map (LRIS, 2012). The model predicted an average increase in peak flood flow of 0.3% and 0.2%, respectively. There appeared to be no correlation between the magnitude of the predicted change in peak flow and the magnitude of the peak flow for each event.

During the development of experimental catchments at Big Bush, northwest South Island, the DC1 and DC4 catchments were cleared of primarily native forest and replanted in pine. The DC1 catchment, with an area of 8.6 ha, was cleared across 83% of its area. The DC4 catchment, with an area of 20.2 ha, was clearfelled across 94% of its area. It was observed that flood flows (per unit area) in the two catchments were generally larger than flood flows in the 4.8 ha DC2 control catchment following the clearing of forest. The increase in flood flow for the smallest flood events was for 77% and 52% for the DC1 and DC4 catchments, respectively. The increase in flood flow for the largest observed flood event was 73% and 26% for the DC1 and DC4 catchments, respectively (Fahey & Jackson, 1997). This increase, albeit as a result of deforestation over a considerably larger proportion of the each catchment, is significantly larger than the increase in flood peaks predicted by the TopNet model in the Pelorus River catchment.

Given the results of the Big Bush experimental catchment, it might have been expected that the increase in peak flood flow predicted by the TopNet model for the Pelorus River catchment would be larger. The clearfelling of forest cover was simulated in the model by removing the canopy capacity in the affected areas, which caused all the precipitation to fall to the ground and generate runoff. However, the deforestation was applied near the outflow of the Pelorus River catchment. This may have resulted in the runoff generated by the deforested area of the catchment flowing out of the catchment before it could contribute to larger flood flows. If the headwaters of the catchment were to undergo clearfelling, it might be expected that the increase in peak flood flow would be more significant as the increased runoff would be routed through the channels and contribute to a larger flood event. Hence, further investigation into clearfelling in the headwaters of the Pelorus River catchment, and other areas of the catchment that may decrease the catchment time to concentration, may yield larger increases in flood flows that agree more closely with past experimental findings.

The conversion of exotic and native forest to agricultural land has been an important historical land use change in New Zealand. Conversion of forested land for agricultural use has occurred over significant areas of catchments across the country; hence the TopNet model was modified to simulate conversion to pasture across 23% and 42% of the Pelorus River catchment. The model predicted an increase in peak flood flow of 0.5% and 0.8%, respectively. It has been established that the conversion of a forest cover to agriculture and pasture results in an increase in water yield in the catchment, however there appears to be limited research regarding the effect on flood peaks.

The TopNet model was used to simulate the conversion of forest to intensive agriculture in the Waikato Region. The results of the model simulations found that conversion of forest to agriculture resulted in a generally consistent per cent increase in peak flow for events on each river between the 5-year return period and the 500-year return period. The increase in peak flow ranged from 1% in the least sensitive Ohakuri River catchment to 12% in the Arapuni River catchment (Woods et al., 2009). The Waikato catchments modelled by TopNet displayed a larger increase in peak flow due to the conversion of forest to agriculture when compared to the TopNet model predictions for the Pelorus River catchment. Another study found that the catchment-wide conversion of native forest to pasture in the Purukohukohu Experimental Basin, Waikato, caused a significant increase in flood peaks (Fahey & Rowe, 1992). Given the results of the TopNet simulations of land use change in the Waikato Region and other studies it may have been expected that the conversion of 23% and 42% of the Pelorus River catchment to pasture would result in a greater increase in flood flow than 0.5% and 0.8%, respectively. The small increase may be partly due to the concentration of land use change near the catchment outflow, where the land is less steep and more suited to agricultural activities. As discussed, the harvest of forest in the Pelorus River catchment yielded similar findings.

Upon comparing the results of the simulated land use change scenarios with previous studies on the effects of land use change on flood hydrology, it appeared that the TopNet model was able to predict the effects of land use change on hydrology, but the predictions may have been very conservative. In all case studies considered, the magnitude of change in flood peak was considerably larger than that predicted by the TopNet model in the Ahuriri and Pelorus River catchments. It was noted that the case study catchments were less steep and significantly smaller than the Ahuriri and the Pelorus River catchments. Some research has been done to establish a relationship between topographical properties, ecological properties such as vegetation cover, and soil properties in the runoff generation hierarchy (For example: Becker & McDonnell, 1998; Fujimoto, Ohte, & Tani, 2011; Jensco & McGlynn, 2011). All have identified a relationship between catchment topography and vegetation cover, but there are a number of other factors such as stream network connectivity and basin type that influence runoff generation. Hence, it is difficult to identify whether runoff in the steep Ahuriri River catchment and Pelorus River catchment is dominated more by topography or by vegetation cover. However, given the small change predicted by the TopNet model given significant land use change, the steep topography of the catchments may influence runoff generation more heavily than vegetation cover.

The determination of a suitable value for saturated hydraulic conductivity K_S to reflect land use change was more subjective and likely to be more uncertain than the values for the canopy storage capacity and the canopy evaporation enhancement factor parameters in the TopNet model. While there was a range of past studies to draw from regarding the effect of land cover on K_S, the studies generally indicated that both land cover and soil properties have a significant effect on K_S (Halabuk, 2005; Karvonen et al., 1999; Lal, 1996; Zimmermann et al., 2006). Furthermore, the studies described a wide range over which K_S varied with land use change. The change in K_S due to different land use changes used for this research project appeared reasonable given the results of past studies. However, the simple sensitivity analysis suggested that K_S had a significant effect on the flood peak prediction. K_S was varied, while canopy storage capacity and canopy evaporation enhancement factor were constant and as described for the conversion from tussock to pasture over 40% of the Ahuriri River catchment (Table 3-6). When K_S was unchanged from the initial model for the Ahuriri River catchment, the change in flood peak could be attributed to the change in canopy storage capacity and canopy evaporation enhancement factor. The increase in flood peak under such conditions was 1.4% on average. When K_S was doubled, or increased by 100%, the flood peak increased by 2.6%, on average, from the unmodified catchment. When K_S was increased by 200% from the original conditions, flood peak increased by 3.2% on average (Table 4-6, Figure 4-27). Hence, the effect of K_S on the prediction of peak flood flow was significant and the increase in K_S was likely responsible for a large proportion of the increase in flood peak. Given the significant of K_S in the TopNet model, any error in K_S in the initial model, possibly as a result of the source of the spatial data used to develop the model, could be responsible for some error in the model predictions. While the calibration of the model should reduce the effect of such error, further investigation into the soil properties of the Ahuriri and Pelorus River catchments may be required to improve the accuracy of the model predictions and reduce the uncertainty in determining suitable values of K_S for the original catchment model and the effects of land use change.

The aforementioned studies have also indicated that soil matrix characteristics and bedrock orientation may have a significant effect on runoff generation in a catchment. While this is less likely to have a strong influence on storm runoff and flood flows, further investigation into the representation of soil characteristics in the TopNet models may be appropriate. It is possible that the methodology by which land use change was simulated in the TopNet model was not wholly appropriate, despite recommendation in earlier investigations (Woods et al., 2009). While it was determined that TopNet is sensitive to saturated hydraulic conductivity, identified by Woods et al. (2009) as the parameter likely to have the most significant effect on the model, investigation into the sensitivity of the model to the canopy storage capacity parameter and the canopy enhancement factor is recommended. Other calibrated parameters, such as the overland flow velocity, which may be influenced by surface roughness and land cover, channel roughness or Manning's *n*, and evaporation enhancement due to land cover, were not considered significant when modelling land use change in TopNet (Woods et al., 2009). However, further investigation into the sensitivity of these parameters may improve the ability of the TopNet model to predict the effects of land use change. Despite the apparent conservative nature of the TopNet model when predicting the effects of land use change on flood hydrology in the steep Ahuriri and Pelorus River catchments when compared to past studies investigating land use change, the model shows the potential to be a useful tool for evaluating the effects of land use change. Provided the rainfall input data is accurate, and following further investigation into model parameter sensitivity and the physical representation of catchment characteristics such as soil, the model may yet prove a valuable asset for land use and water resource management in mountainous catchments in New Zealand.

4.4 Potential Implications for Resource Management in New Zealand

A 2008 report by the New Zealand Ministry for the Environment (MFE) into the challenges of future flooding in New Zealand identified flooding as the most widespread natural hazard likely to affect population and infrastructure (MFE, 2008). The report also identified land use and the conditions upstream in a catchment as important factors in determining flood risk. Physical structures such as levees and stopbanks are a widespread method of flood risk reduction in New Zealand; however such measures may not be the best measures for flood prevention. The structures require maintenance, and are only effective up to a certain level of flood, beyond which emergency flood measures must be taken (MFE, 2008). Instead, MFE recommended that regional authorities adopt "holistic catchment management that integrates flooding from all sources and the impacts of catchment land use" (p. 11). A 2011 report for the New Zealand Institute of Geological and Nuclear Sciences (GNS) identified the need for improvements in flood forecasting tools as a key area for future research to address flood risk management in New Zealand (Rouse, 2011). The report also recommended a push toward integrated catchment management, whereby flood risks are integrated with water and land management strategies to fulfil legal obligations under the RMA. Following the outcomes of this research project, the TopNet model may be able to be improved and used for effective flood forecasting in New Zealand. Furthermore, hydrologic modelling is a key part of integrated catchment management. TopNet has shown the potential to be able to predict flood flows and the effects of land use change on flood hydrology, and may be a useful addition to an integrated catchment management scheme.

The RMA is the overarching legislation governing the management of natural resources, including fresh water, in New Zealand. Important sections of the RMA that pertain to freshwater resources and land use change include Section 30(c), which assigns regional or unitary authorities the responsibility to control land for the avoidance or mitigation of natural hazards, and Section 30(g), which assigns regional or unitary authorities the responsibility to control the bed of a water body for the avoidance or mitigation of natural hazards. Section 31 of the RMA assigns territorial or city authorities responsibility to control the effects of land use and development for the avoidance or mitigation of natural hazards. It can be argued that the division of responsibility between the regional authorities and territorial authorities has hindered the effective management of some resources (Painter, 2004). It can also be argued that the RMA has been enforced with a sense of ambiguity toward stakeholders in some cases, such as in the UWB (Addison, 2009). However, an accurate and widely available tool to model flood flows and the influence of land use change on flood hydrology could reduce the uncertainty regarding water and land use policy in some areas.

In general, flooding may not pose a significant hazard in mountainous catchments in New Zealand because they are often sparsely populated and have little infrastructure. However, the downstream effects of land use change in the upper reaches of a catchment may be significant and should be considered (MFE, 2008). For example, the Clutha River in Otago and the Waitaki River bordering Otago and Canterbury each have sparsely populated mountainous headwaters, but heavy rain in the headwaters has contributed to significant flooding downriver (Waugh, Freestone, & Lew, 1997). The model predicted the flood flow for large events well, provided the rainfall input was accurate in temporal and spatial distribution. Hence, the TopNet model may be a useful tool for predicting flood flows in mountainous catchments and may be considered in flood management strategy.

The aforementioned reports also identified land use change as an important factor in flood risk. Local governments have tended to focus on the effect of land use change on water balance, catchment yield, and low flows. These are important considerations for the effective management of water resources in New Zealand, but regional or unitary authorities may neglect the impact land use change has on the flood characteristics of a catchment, which may affect the level of flood hazard in a catchment and downstream of the catchment. This may be a result of poor understanding of flood mechanisms or a lack of effective tools for analysing land use change. Nevertheless, given the significant changes to flood characteristics observed in past studies of land use change in a catchment, it may be an important consideration for future land use management. The TopNet model has shown the ability to predict the effects of land use change on flood hydrology, although the predictions may have been conservative. Hence, TopNet may be a useful tool in flood risk management, but further investigation and model development may be recommended.

The TopNet model appeared to predict the effects of land use change very conservatively when compared to the results of past studies. This suggests that while the model shows promise, it requires more work. Studies have indicated that:

- Converting forested land to pasture may significantly increase flood flows;
- Clearfelling forested land may significantly increase flood flows;
- Converting tussock grassland to managed pasture may increase flood flows; and
- Reforestation of tussock grassland may significantly reduce flood flows.

However, these studies were conducted in less steep, low-altitude catchments and so may not reflect the behaviour of the Ahuriri River catchment and the Pelorus River catchment. If the TopNet model predictions were accurate it could be argued that the effect of land use change on the flood hydrology of the catchments is almost negligible, and so may not need to be considered when managing future land use in steep catchments in New Zealand, and instead factors such as catchment topography, pedology, and geology may be more significant. Further testing and development of the TopNet model, coupled with further research into the flood hydrology of mountainous catchments and land use change in New Zealand should improve the understanding of mountainous catchments and enable TopNet to become a more useful tool for assessing land use change.

Catchments in the UWB can be expected to behave similarly to the Ahuriri River catchment, with the exception of the lower reaches of catchments influenced by HEP generation, including reservoir lakes and dams. The UWB has been subject to numerous competing claims for water resources from a wide variety of stakeholders, including power companies, farmers, and environmental groups (Addison, 2009). The Resource Management (Waitaki Catchment) Amendment Act 2004 and the consequent Waitaki Catchment Water Allocation Plan were enacted in an attempt to resolve ambiguity in the legislation governing water rights in the UWB. Following analysis of the legislation and planning strategy Addison (2009) argued that the measures had "not provided clarity on water allocation in the region" (p. 25). While the Waitaki Catchment Water Allocation Plan made specific mention of applying a lower limit to low flows in Policy 7, it did not appear to consider the effects of land use change and land management on flood flows in the UWB; rather it went only so far as stating the importance of flood management without any further elaboration. Increasing flood risk is not permitted under the RMA, and restricting land uses that may increase flood risk may reduce the level of conflict over land and water in the UWB. The TopNet model predicted insignificant changes in flood flows for the potential land use scenarios in the Ahuriri River catchment, and this could be extrapolated to the UWB such that land use change may not be expected to change flood risk in the area. However, further testing and improvement of the TopNet model may yield more reliable and significant results, and may prove to be a useful tool in aiding land use management in the UWB.

5 Conclusions

One objective of this research project was to determine whether TopNet, a hydrologic model developed for the continuous modelling of catchments and catchment networks, was able to accurately predict flood flows in steep river catchments in New Zealand. The models used in the investigation were developed by NIWA for the Ahuriri and Pelorus River catchments, in the South Island of New Zealand. It was found that the TopNet model was able to predict flood flows with a high level of accuracy. However, this depended heavily on the accuracy of the rainfall estimated by the VCSN and input to the model. Precipitation input has been identified as a key input to a hydrologic model, and this is true for the TopNet model when predicting flood flows. The Ahuriri River catchment model showed the most accurate flood predictions when the daily rainfall estimate from the VSCN was disaggregated by the model into hourly rainfall based on observed rainfall from gauges within the catchment. When the daily rainfall estimate was disaggregated to hourly rainfall using a stochastic distribution, the flood predictions were significantly less accurate. The TopNet model for the Pelorus River catchment was generally inaccurate. This may have been a result of poor rainfall estimates from the VCSN, which resulted in erroneous flood prediction regardless of the accuracy of the numerical approximation of physical processes acting within the catchment. Further testing of the TopNet model and rainfall input methods to the model has been recommended in order to quantify the effect of rainfall input on the ability of TopNet to model flood flows, and to better understand and quantify the accuracy and effect of the VCSN in mountainous regions.

A selection of high flow events from the historical flow record for the Ahuriri River and the Pelorus River were also modelled in order to assess the accuracy of the TopNet model for predicting a range of flood magnitudes. The daily rainfall estimate from the VCSN for each event was disaggregated into hourly rainfall based on observed rainfall data for the Ahuriri River catchment model and stochastically for the Pelorus River catchment model. The TopNet model for the Pelorus River catchment, as discussed, displayed significant error that may have been a result of poor rainfall input to the model. The model significantly underpredicted all flood events modelled, with an average error in peak flow prediction of 69%. The Ahuriri River model appeared to underpredict flood events with ARI less than 5 years by an average of 44%. However, the model accurately predicted larger flood events. Floods with ARI greater than 5 years were predicted with an average error in peak flow of 2.4%. Hence, it could be concluded that the TopNet model was able to accurately predict large flood flows in mountainous catchments, provided the rainfall input to the model was an accurate estimate of actual rainfall. Further research could include the modelling of more high flow events using different rainfall input methods, and the modelling of high flow events in other mountainous catchments using the TopNet model.

The TopNet models were also used to simulate the effect of land use changes on the flood hydrology of the Ahuriri River catchment and the Pelorus River catchment. The land use scenarios modelled in the Ahuriri River catchment were: the conversion of unmanaged tussock grassland to pasture, and native reforestation of the river catchment. The land use scenarios modelled in the Pelorus River catchment were: the clearfelling and harvest of plantation forestry, and the conversion of forest to pasture. The TopNet model predicted that the conversion of between 22% and 40% of the Ahuriri River catchment to pasture would increase the peak flood flow between 0.7% and 2.6%. Most studies into the hydrological effects of the pastoralisation of unmanaged land have suggested that the increase in peak flood flow should have been significantly larger. The findings were similar for all land use change scenarios modelled. The model predicted that the reforestation of the Ahuriri River catchment would decrease flood peaks by a small amount. Past investigations found such a land use change to have a significantly larger influence on the magnitude of flood peaks. The TopNet model predicted that the clearfelling of plantation forestry in the Pelorus River catchment would increase peak flows, but past studies into the effects of forestry harvest and deforestation have suggested that the increase should have been significantly larger. Overall, the TopNet model predicted the direction of the change in peak flood flows accurately, but it could be argued that the magnitudes of the changes were significantly underpredicted. While the TopNet model showed potential to be a useful tool in the management of land use change and flood risk, further investigation into the methodology of simulating land use change in the model may improve the ability of TopNet to predict the effects of land use change. The results of the simulation of land use change also indicated that the topography, geology, and pedology of a catchment may have a more significant effect on flood hydrology than land cover and vegetation in the TopNet model. However, it was shown that the model can be influenced significantly by saturated hydraulic conductivity K_S. Further investigation into parameter sensitivity, other parameters that may represent land use change in a catchment, and appropriate values for parameters that are specific to each catchment, such as K_S, is recommended.

References

Adams, R., Parkin, G., Rutherford, J. C., Ibbitt, R. P., & Elliott, A. H. (2005). Using a rainfall simulator and a physically based hydrological model to investigate runoff processes in a hillslope. *Hydrological Processes, 19*(11), 2209-2223.

Addison, V. (2009). *Water allocation and the sustainability of dairying in the Upper Waitaki River Basin.* Master in Environmental Studies Thesis, Victoria University, Wgtn.

Andrew, T., & Richard, T. (2005). Generating multiyear gridded daily rainfall over New Zealand. *Journal of Applied Meteorology, 44*(9), 1315-1323.

Aqualinc (2008). Irrigation and drainage modelling of the Upper Waitaki Basin: GHD Limited.

Aqualinc (2010). Update of water allocation data and estimate of actual water use of consented takes 2009-10: Ministry for the Environment.

Asaad, S. (2005). Topics related to rainfall-runoff models *River Basin Modelling for Flood Risk Mitigation* (pp. 171-180): Taylor & Francis.

Bandaragoda, C., Tarboton, D. G., & Woods, R. (2004). Application of TOPNET in the distributed model intercomparison project. *Journal of Hydrology, 298*(1-4), 178-201.

Bari, M. A., Smith, N., Ruprecht, J. K., & Boyd, B. W. (1996). Changes in streamflow components following logging and regeneration in the southern forest of Western Australia. *Hydrological Processes, 10*(3), 447-461.

Becker, A., & McDonnell, J. J. (1998). Topographical and ecological controls of runoff generation and lateral flows in mountain catchments. *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences, 248,* 199-206.

Beven, K. (1979). On the generalized kinematic routing method. *Water Resour. Res., 15*(5), 1238-1242.

Beven, K., & Kirkby, M. J. (1979). Physically based, variable contributing area model of basin hydrology. *Hydrological Science Bulletin, 24*(1), 43-69.

Brown, I., & Harris, S. (2005). Environmental, economic, and social impacts of irrigation in the Mackenzie Basin: Ministry for the Environment.

Campbell, D. I., & Murray, D. L. (1990). Water balance of snow tussock grassland in New Zealand. *Journal of Hydrology, 118*(1–4), 229-245.

Cao, W., Bowden, W., Davie, T., & Fenemor, A. (2009). Modelling impacts of land cover change on critical water resources in the Motueka River catchment, New Zealand. *Water Resources Management, 23*(1), 137-151.

Caruso, B. S. (2006). Effectiveness of braided, gravel-bed river restoration in the Upper Waitaki Basin, New Zealand. *River Research and Applications, 22*(8), 905-922.

Caruso, B. S., Rademaker, M., Balme, A., & Cochrane, T. A. (2013). Flood modelling in a high country mountain catchment, New Zealand: comparing statistical and deterministic model estimates for ecological flows. *Hydrological Sciences Journal, 58*(2), 1-14.

Colley, M. (Ed.). (2005). *Forestry Handbook*. Chch: New Zealand Institute of Forestry.

Cunderlink, J., & Simonovic, S. (2004). *Calibration, verification, and sensitivity analysis of the HEC-HMS hydrologic model: Project report IV*. London, Ontario.

Currie, J. D. (1974). Farming in North Otago. *Proceedings of the N.Z. Grassland Association, 36*.

Davie, T. (2004). Soil water, runoff, and streamflow generation. In J. S. Harding, P. Mosley, C. Pearson & B. Sorrell (Eds.), *Freshwaters of New Zealand*. Chch, NZ: New Zealand Hydrological Society Inc.

Davis, J. (1996). Dairying - Waitaki's opportunity. *Proceedings of the N.Z. Grassland Association, 58*, 119-122.

DHI (Danish Hydraulic Institute) (2007). Mike SHE User Manual Volume 1: User Guide: DHI Water and Environment.

DHI (Danish Hydraulic Institute) (2009). Mike 11: User guide: DHI Water and Environment.

Duncan, M. J. (1980). *The impact of afforestation of small-catchment hydrology in Moutere Hills, Nelson*. Paper presented at the Seminar on Land-use in Relation to Water Quantity and Quality, Nelson, New Zealand.

Duncan, M. J. (1995). Hydrological impacts of converting pasture and gorse to pine plantation, and forest harvesting, Nelson, New Zealand. *Journal of Hydrology (N.Z.), 34*, 15-41.

ECan (Environment Canterbury) (2009). Canterbury Natural Resources Regional Plan. Christchurch: Environment Canterbury.

Edlin, B. (2001). Forestry's race for gold. *New Zealand Management, 48*(9), 56-56.

Esling, S. P., DeVantier, B. A., Zeng, X., & McDonald, T. (2000). *An investigation of temporal changes in soil permeability within the vadose zone of areas inundated by floods.* Paper presented at the Illinois Groundwater Consortium Conference, Makanda, IL.

EW (Environment Waikato) (2010). Summary of the effects of land use change between Taupo and Karapiro on the flood hydrology of the Waikato River Catchment. Hamilton, NZ: Environment Waikato.

Ewen, J., Parkin, G., & O'Connell, P. (2000). SHETRAN: Distributed river basin flow and transport modeling system. *Journal of Hydrologic Engineering, 5*(3), 250-258.

Fahey, B. D. (1994). The effect of plantation forestry on water yield in New Zealand. *New Zealand Journal of Forestry, 39*(3), 18-25.

Fahey, B. D., Davie, T., & Stewart, M. (2011). The application of a water balance model to assess the role of fog in water yields from catchments in the east Otago uplands, south island, New Zealand. *Journal of Hydrology (N.Z.), 50*(2), 297-292.

Fahey, B. D., Duncan, M. J., & Quinn, J. (2004). Impacts of forestry. In J. S. Harding, P. Mosley, C. Pearson & B. Sorrell (Eds.), *Freshwaters of New Zealand*. Chch, NZ: New Zealand Hydrological Society Inc.

Fahey, B. D., Ekanayake, J., Jackson, R., Fenemor, A., Davie, T., & Rowe, L. (2010). Using the WATYIELD water balance model to predict catchment water yields and low flows. *Journal of Hydrology (N.Z.), 49*(1), 35-58.

Fahey, B. D., & Jackson, R. (1997). Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. *Agricultural and Forest Meteorology, 84*(1–2), 69-82.

Fahey, B. D., Jackson, R. J., & Davie, T. J. A. (2004). User’s guide for the Land Use Change Water Balance Model (WATYIELD). Lincoln: Landcare Research.

Fahey, B. D., & Rowe, L. K. (1992). Land-Use Impacts. In P. Mosley (Ed.), *Waters of New Zealand*. Chch, NZ: New Zealand Hydrological Society.

Fahey, B. D., Watson, A. J., & Payne, J. (2001). Water loss from plantations of Douglas-fir and radiata pine on the Canterbury Plains, South Island, New Zealand. *Journal of Hydrology (N.Z.), 40*(1), 77-96.

Fisher, R. M., & Russell, F. (2011). Water policy and regulatory reform in New Zealand. *International Journal of Water Resources Development, 27*(2), 387-400.

Freer, J. E., McMillan, H., McDonnell, J. J., & Beven, K. J. (2004). Constraining dynamic TOPMODEL responses for imprecise water table information using fuzzy rule based performance measures. *Journal of Hydrology, 291*(3–4), 254-277.

Fujimoto, M., Ohte, N., & Tani, M. (2011). Effects of hillslope topography on runoff response in a small catchment in the Fudoji Experimental Watershed, central Japan. *Hydrological Processes, 25*(12), 1874-1886.

Funk, J. (2009). *Carbon farming in New Zealand: An interdisciplinary assessment of indigenous reforestation as a land-use system.* Stanford University, Cal, USA.

Garr, C. E., & Fitzharris, B. B. (1991). A climate classification of New Zealand based on numerical techniques. *New Zealand Geographer, 47*(2), 60-71.

Gentry, A. H., & Lopez-Parodi, J. (1980). Deforestation and increased flooding of the Upper Amazon. *Science, 210*(4476), 1354-1356.

Gonçalves, R. A. B., Folegatti, M. V., Gloaguen, T. V., Libardi, P. L., Montes, C. R., Lucas, Y., . . . Melfi, A. J. (2007). Hydraulic conductivity of a soil irrigated with treated sewage effluent. *Geoderma, 139*(1–2), 241-248.

Green, W., & Ampt, G. (1911). Studies on soil physics. Part I: The flow of air and water through soils. *Journal of Agricultural Science, 4*(1), 1-24.

Griffiths, G. A., & Ross, P. (1997). Principles of managing extreme events. In P. Mosley & C. Pearson (Eds.), *Floods and Droughts: the New Zealand Experience*. Chch, NZ: New Zealand Hydrological Society Inc.

Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology, 377*(1–2), 80-91.

Guzha, A., & Hardy, T. (2010). Application of the distributed hydrological model, TOPNET, to the Big Darby Creek Watershed, Ohio, USA. *Water Resources Management, 24*(5), 979-1003.

Halabuk, A. (2005). Influence of different land use on saturated hydraulic conductivity in alluvial landscape. *Geophysical Research Abstracts, 7*.

Hewlett, J., & Hibbert, A. (1967). Factors affecting the response of small watersheds to precipitation in humid areas. In W. Sopper & H. Lull (Eds.), *Forest Hydrology* (pp. 275-290). Pergamon, NY.

Holko, L., & Lepisto, A. (1997). Modelling the hydrological behaviour of a mountain catchment using TOPMODEL. *Journal of Hydrology, 196*(1-4), 361-377.

Horrell, G. A., McKerchar, A. I., Griffiths, G. M., & Griffiths, G. A. (2012). South Island storms and floods of December 2010. *Journal of Hydrology (N.Z.), 51*(1), 63-81.

Horton, R. (1933). The role of infiltration in the hydrological cycle. *Transactions of the American Geophysical Union, 14*.

Ibbitt, R. P. (1971). Development of a conceptual model of interception, Unpublished Hydrological Research Progress Report No. 5. New Zealand: Ministry of Works.

Ibbitt, R. P., McKerchar, A., & Woods, R. (2004). Catchments, streamflow and the use of models. In J. S. Harding, P. Mosley, C. Pearson & B. Sorrell (Eds.), *Freshwaters of New Zealand*. Chch, NZ: New Zealand Hydrological Society Inc.

Ibbitt, R. P., Thompson, C., & Turner, R. (2005). Skill assessment of a linked precipitation-runoff flood forecasting system. *Journal of Hydrology (N.Z.), 44*(2), 91-104.

Iorgulescu, I., & Jordan, J. P. (1994). Validation of TOPMODEL on a small Swiss catchment. *Journal of Hydrology, 159*(1-4), 255-273.

Iroumé, A., Mayen, O., & Huber, A. (2006). Runoff and peak flow responses to timber harvest and forest age in southern Chile. *Hydrological Processes, 20*(1), 37-50.

Ives, J. D. (1989). Deforestation in the Himalayas: The cause of increased flooding in Bangladesh and Northern India? *Land Use Policy, 6*(3), 187-193.

Jain, S., & Sudheer, K. (2008). Fitting of hydrologic models: A close look at the Nash–Sutcliffe Index. *Journal of Hydrologic Engineering, 13*(10), 981-986.

Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resour. Res., 47*(11), W11527.

Jones, J. A., & Grant, G. E. (1996). Peak flow responses to clear-cutting and roads in small and large basins, Western Cascades, Oregon. *Water Resources Research, 32*(4), 959-974.

Karvonen, T., Koivusalo, H., Jauhiainen, M., Palko, J., & Weppling, K. (1999). A hydrological model for predicting runoff from different land use areas. *Journal of Hydrology, 217*(3–4), 253-265.

Kienzle, S. W., & Schmidt, J. (2008). Hydrological impacts of irrigated agriculture in the Manuherikia Catchment, Otago, New Zealand. *Journal of Hydrology (N.Z.), 47*(2), 67-84.

Lal, R. (1996). Deforestation and land-use effects on soil degradation and rehabilitation in western Nigeria. I. Soil physical and hydrological properties. *Land Degradation & Development, 7*(1), 19-45.

Lamb, R. (1999). Calibration of a conceptual rainfall-runoff model for flood frequency estimation by continuous simulation. *Water Resources Research, 35*(10), 3103-3114.

Liu, J., & Han, D. (2010). Indices for calibration data selection of the rainfall-runoff model. *Water Resources Research, 46*(4).

LRIS (Land Resource Information Systems) (2012). LRIS Portal. Retrieved 2012, from Landcare Research New Zealand Ltd http://lris.scinfo.org.nz

MacLeod, C. J., & Moller, H. (2006). Intensification and diversification of New Zealand agriculture since 1960: An evaluation of current indicators of land use change. *Agriculture, Ecosystems & Environment, 115*(1–4), 201-218.

MAF (Ministry of Agriculture and Forestry) (2011). National exotic forest description. Wgtn: Ministry of Agriculture and Forestry.

Marden, M., Arnold, G., Seymour, A., & Hambling, R. (2012). History and distribution of steepland gullies in response to land use change, East Coast Region, North Island, New Zealand. *Geomorphology, 153–154*(0), 81-90.

Mays, L. W. (2011). *Water resources engineering* (2nd ed.). Hoboken, NJ: John Wiley.

McCuen, R., Knight, Z., & Cutter, A. (2006). Evaluation of the Nash–Sutcliffe Efficiency Index. *Journal of Hydrologic Engineering, 11*(6), 597-602.

McMillan, H., & Clark, M. (2009). Rainfall-runoff model calibration using informal likelihood measures within a Markov chain Monte Carlo sampling scheme. *Water Resources Research, 45*(4).

McMillan, H., Jackson, B., Clark, M., Kavetski, D., & Woods, R. (2011). Rainfall uncertainty in hydrological modelling: An evaluation of multiplicative error models. *Journal of Hydrology, 400*(1–2), 83-94.

MDC (Marlborough District Council) (2009a). North Marlborough significant natural areas project. Blenheim: Marlborough District Council.

MDC (Marlborough District Council) (2009b). Wairau/Awatere Resource Management Plan. Blenheim: Marlborough District Council.

Mediero, L., Garrote, L., & Martín-Carrasco, F. J. (2011). Probabilistic calibration of a distributed hydrological model for flood forecasting. *Hydrological Sciences Journal, 56*(7), 1129-1149.

MFE (Ministry for the Environment) (2008). Meeting the challenges of future flooding in New Zealand. Wgtn, NZ: Ministry for the Environment.

MFE (Ministry for the Environment) (2010). Preparing for future flooding. Wgtn, NZ: Ministry for the Environment

Mosley, P. (Ed.). (1992). *Waters of New Zealand*: New Zealand Hydrological Society.

MPI (Ministry for Primary Industries) (2012). Situation and outlook for primary industries 2012. Wgtn: Ministry for Primary Industries.

Mubarak, I., Mailhol, J. C., Angulo-Jaramillo, R., Ruelle, P., Boivin, P., & Khaledian, M. (2009). Temporal variability in soil hydraulic properties under drip irrigation. *Geoderma, 150*(1–2), 158-165.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology, 10*(3), 282-290.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). Soil water assessment tool theoretical documentation. Texas: Texas A&M University.

Newsome, P., Wilde, R., & Willoughby, E. (2008). Land Resource Information System Spatial Data Layers: Data Dictionary. Palmeston North, N.Z.: Landcare Research New Zealand Ltd.

NIWA (National Institute of Water and Atmospheric Research). (2012a). High Intensity Rainfall System V3. Retrieved 2012 http://hirds.niwa.co.nz/

NIWA (National Institute of Water and Atmospheric Research) (2012b). The National Climate Database. Retrieved 2012 http://cliflo.niwa.co.nz/

NRC (Northland Regional Council) (2012). Forestry earthworks and harvesting guidelines for Northland. Whangarei: Northland Regional Council.

OECD (Organisation for Economic Cooperation and Development) (2007). *OECD Environmental Performance Reviews: New Zealand 2007*: OECD Publishing.

Painter, D. (2004). Managing water-related risks. In J. S. Harding, P. Mosley, C. Pearson & B. Sorrell (Eds.), *Freshwaters of New Zealand*. Chch, NZ: New Zealand Hydrological Society Inc.

PCE (Parliamentary Commissioner for the Environment) (2004). *Growing for good*. Wellington: Parliamentary Commissioner for the Environment.

Pearce, A. J., O'Loughlin, C. L., Jackson, R. J., & Zhang, X. B. (1987). Reforestation: on-site effects on hydrology and erosion, eastern Raukumara Range, New Zealand *Forest Hydrology and Watershed Management Publication 167* (pp. 489-497). Wallingford, Oxfordshire: International Association of Hydrological Sciences

Pearson, C., & Henderson, R. D. (2004). Floods and low flows. In J. S. Harding, P. Mosley, C. Pearson & B. Sorrell (Eds.), *Freshwaters of New Zealand*. Chch, NZ: New Zealand Hydrological Society Inc.

Petrow, T., Merz, B., Lindenschmidt, K. E., & Thieken, A. H. (2007). Aspects of seasonality and flood generating circulation patterns in a mountainous catchment in south-eastern Germany. *Hydrology and Earth System Sciences, 11*(4), 1455-1468.

Priestley, C. H. B., & Taylor, R. J. (1972). On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review, 100*(2), 81-92.

Reed, S., Koren, V., Smith, M., Zhang, Z., Moreda, F., Seo, D.-J., & Dmip Participants, a. (2004). Overall distributed model intercomparison project results. *Journal of Hydrology, 298*(1–4), 27-60.

Reid, E. H. (Ed.). (1981). *Rangeland hydrology* (Second ed.). Dubuque, Iowa: Kendall/Hunt.

Rouse, H. (2011). Flood risk management research in New Zealand: Where are we, and where are we going? NZ: GNS Science.

Rowe, L. (2003). Land use and water resources: A comparison of streamfow from New Zealand catchments with different vegetation covers. Report for the Ministry for the Environment. LC0203/188: Landcare Research.

Rowe, L., Fahey, B., & Jackson, R. (2002). Land use and water resources: Hydrological effects of different vegetation covers. Wellington, NZ: Landcare Research New Zealand.

Rowe, L., Fahey, B. D., Jackson, R., & Duncan, M. J. (1997). Effects of land use on floods and low flows. In P. Mosley & C. Pearson (Eds.), *Floods and Droughts: the New Zealand Experience*. Chch, NZ: New Zealand Hydrological Society Inc.

Rowe, L., & Pearce, A. (1994). Hydrology and related changed after harvesting native forest catchments and establishing *Pinus radiata* plantations. Part 2. The native forest water balance and the changes in streamflow after harvesting. *Hydrological Processes, 8*, 281-297.

Scharffenberg, W., & Fleming, M. (2010). Hydrologic Modelling System HEC-HMS User's Manual Version 3.5. Davis, CA: U.S. Army Corps of Engineers Hydrologic Engineering Centre, HEC.

Sherman, L. K. (1932). Streamflow from rainfall by the unit-graph method. *Eng. News Record, 108*, 501-505.

Singh, V. P. (1995). *Computer models of watershed hydrology* (Rev. ed.). Highlands Ranch, Colo.: Water Resources Publications.

Singh, V. P. (2005). Unit Hydrograph Theory. In J. H. Lehr & J. Keeley (Eds.), *Water Encyclopedia* (Vol. 4, pp. 355-360). Hoboken, NJ: Wiley.

SKM (Sinclair Knight Merz) (2012). Regional council practice for setting and meeting RMA-based limits for freshwater flows and quality: Ministry for the Environment.

Smart, G. M., & McKerchar, A. I. (2010). More flood disasters in New Zealand. *Journal of Hydrology (N.Z.), 49*(2), 69-78.

Smith, M., & Gupta, H. (2012). The Distributed Model Intercomparison Project (DMIP) – Phase 2 experiments in the Oklahoma Region, USA. *Journal of Hydrology, 418–419*(0), 1-2.

Smith, M., Koren, V., Zhang, Z., Zhang, Y., Reed, S. M., Cui, Z., . . . Anderson, E. A. (2012). Results of the DMIP 2 Oklahoma experiments. *Journal of Hydrology, 418–419*(0), 17-48.

Smith, P. (1987). Variation of water yield from catchments under introduced pasture grass and exotic forest, East Otago. *Journal of Hydrology (N.Z.), 26*(2), 175-184.

Smith, W., & Montgomery, H. (2004). Revolution or evolution? New Zealand agriculture since 1984. *GeoJournal, 59*(2), 107-118.

Stewart, M. K., & Fahey, B. D. (2010). Runoff generating processes in adjacent tussock grassland and pine plantation catchments as indicated by mean transit time estimation using tritium. *Hydrology and Earth System Sciences, 14*(6), 1021-1032.

Sun, S., & Deng, H. (2004). A study of rainfall-runoff response in a catchment using TOPMODEL. *Advances in Atmospheric Sciences, 21*(1), 87-95.

Tait, A., Sturman, J., & Clark, M. (2012). An assessment of the accuracy of interpolated daily rainfall for New Zealand. *Journal of Hydrology (N.Z.), 51*(1), 25-44.

TDC (Tasman District Council) (2008). Tasman Resource Management Plan. Nelson: Tasman District Council.

Trotter, C., Tate, K., Scott, N., & Townsend, J. (2005). Afforestation/reforestation of New Zealand marginal pasture lands by indigenous shrublands: the potential for Kyoto forest sinks. *Annals of forest science., 62*(8), 865-871.

UNESCO (United Nations Educational, Scientific and Cultural Organisation) (2009). The United Nations world water development report 3: Water in a changing world. London: UNESCO.

Waugh, J., Freestone, H., & Lew, D. (1997). Historic floods and droughts in New Zealand. In P. Mosley & C. Pearson (Eds.), *Floods and Droughts: the New Zealand Experience*. Chch, NZ: New Zealand Hydrological Society Inc.

WCWAB (Waitaki Catchment Water Allocation Board) (2006). Waitaki catchment water allocation regional plan. NZ: Chch: Waitaki Catchment Water Allocation Board.

Woods, R., Schmidt, J., & Collins, D. (2009). Estimating the potential effect of land use change on Waikato tributary floods - TopNet model development. Christchurch, NZ: National Institute of Water and Atmospheric Research.

Young, R., Smart, G. M., & Harding, J. S. (2004). Impacts of hydro-dams, irrigation schemes and river control works. In J. S. Harding, P. Mosley, C. Pearson & B. Sorrell (Eds.), *Freshwaters of New Zealand*. Chch, NZ: New Zealand Hydrological Society Inc.

Zhao, F., Xu, Z., & Zhang, L. (2012). Changes in streamflow regime following vegetation changes from paired catchments. *Hydrological Processes, 26*(10), 1561-1573.

Zimmermann, B., Elsenbeer, H., & De Moraes, J. M. (2006). The influence of land-use changes on soil hydraulic properties: Implications for runoff generation. *Forest Ecology and Management, 222*(1–3), 29-38.

Appendix I: Hydrographs for Land Use Change Scenarios

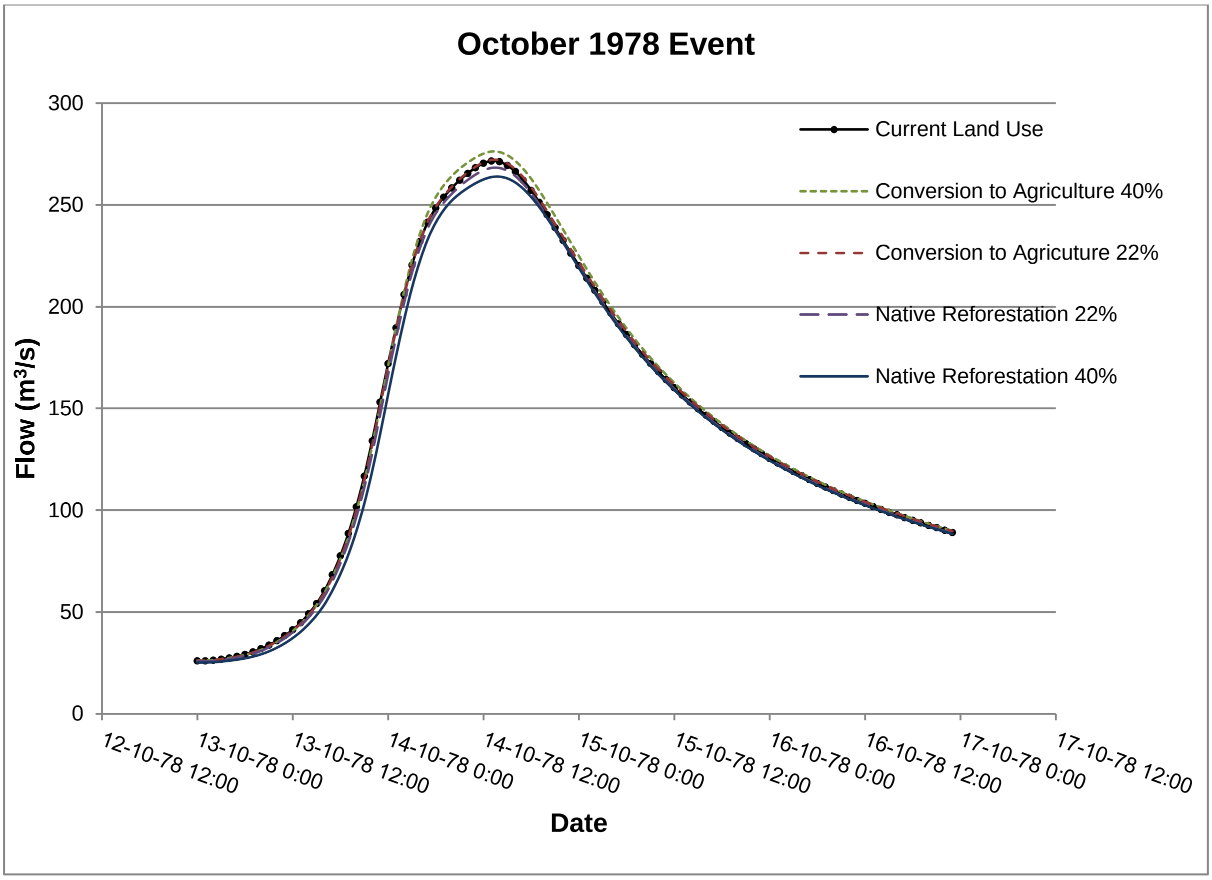
Appendix I pertains to Section 4.3: Modelling Future Land Use Scenarios. The hydrographs show the future land use scenarios modelled for each flood event.

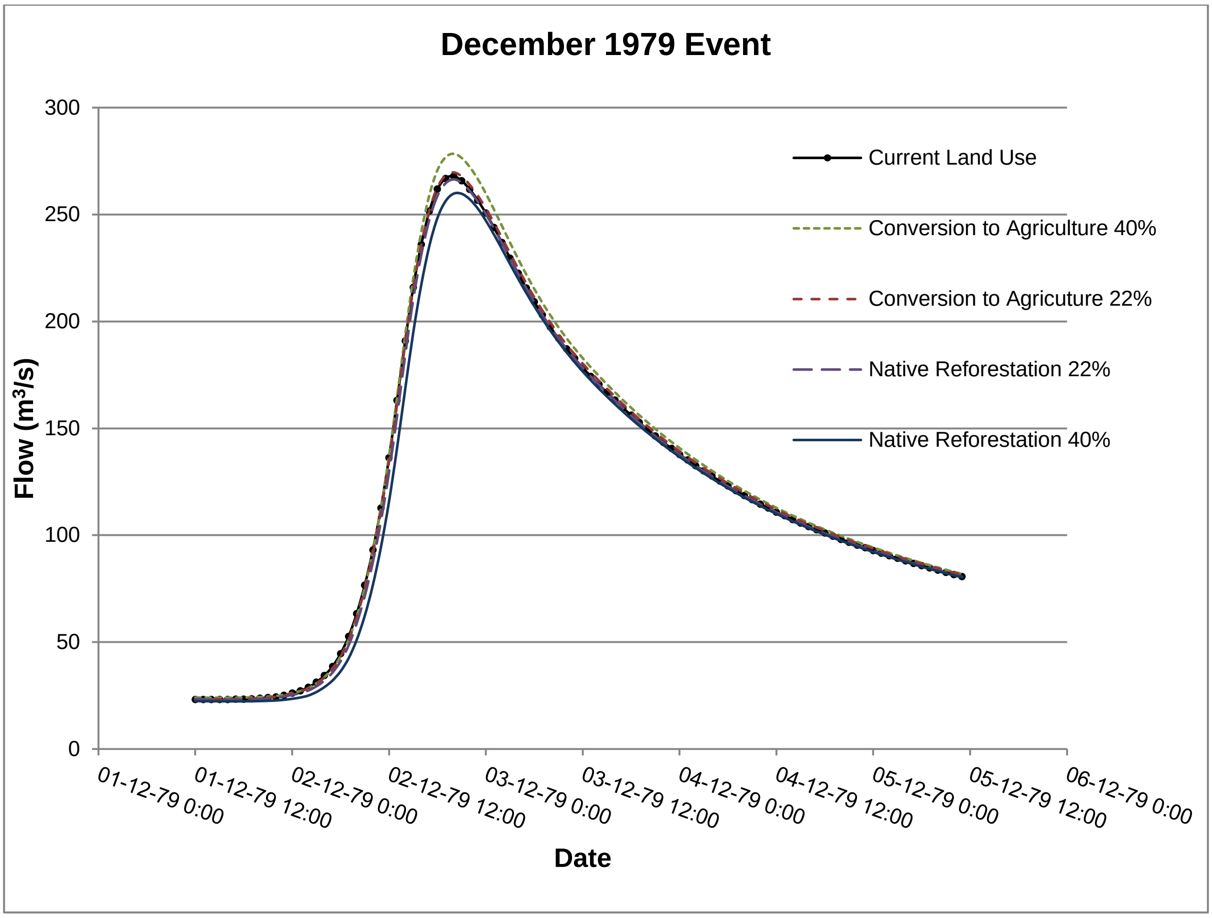
Ahuriri River Catchment

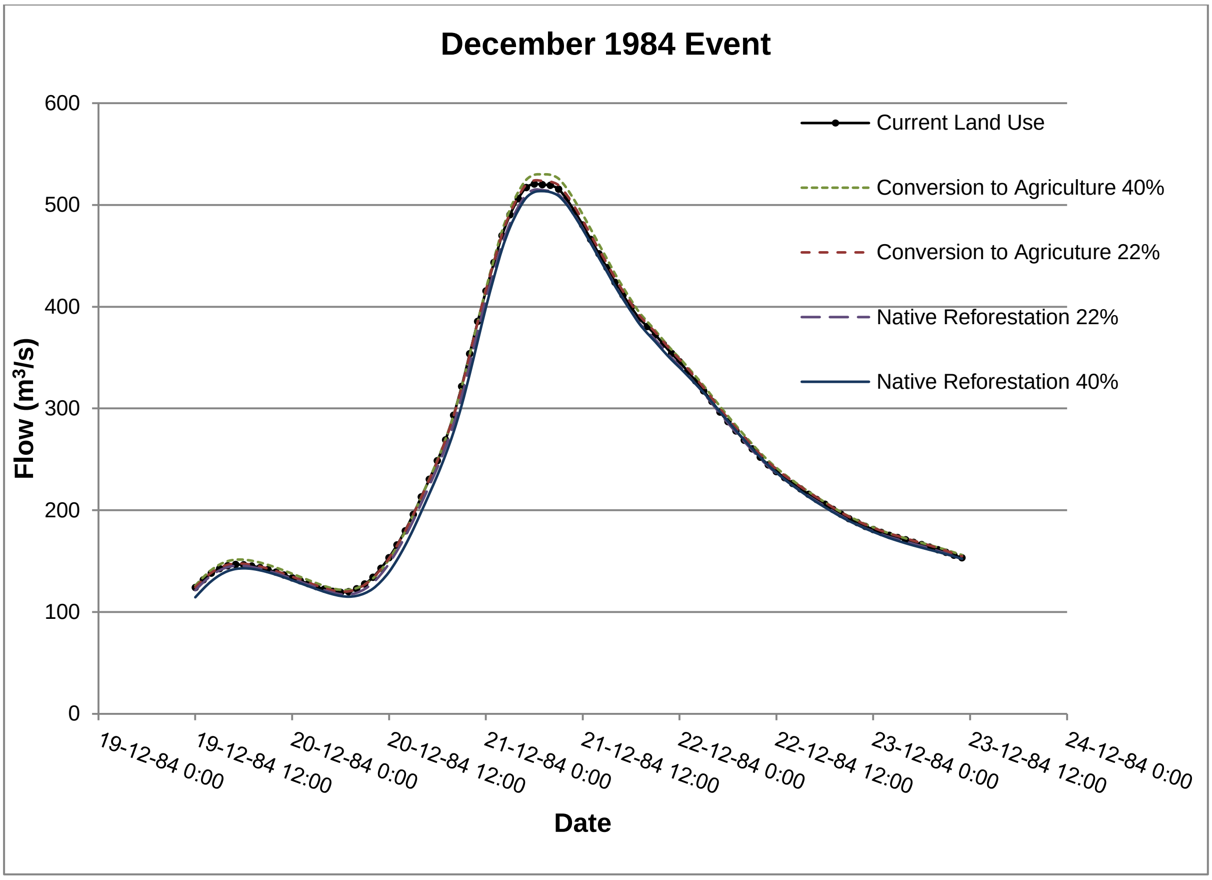
Results of modelling land use change scenarios, Ahuriri River catchment

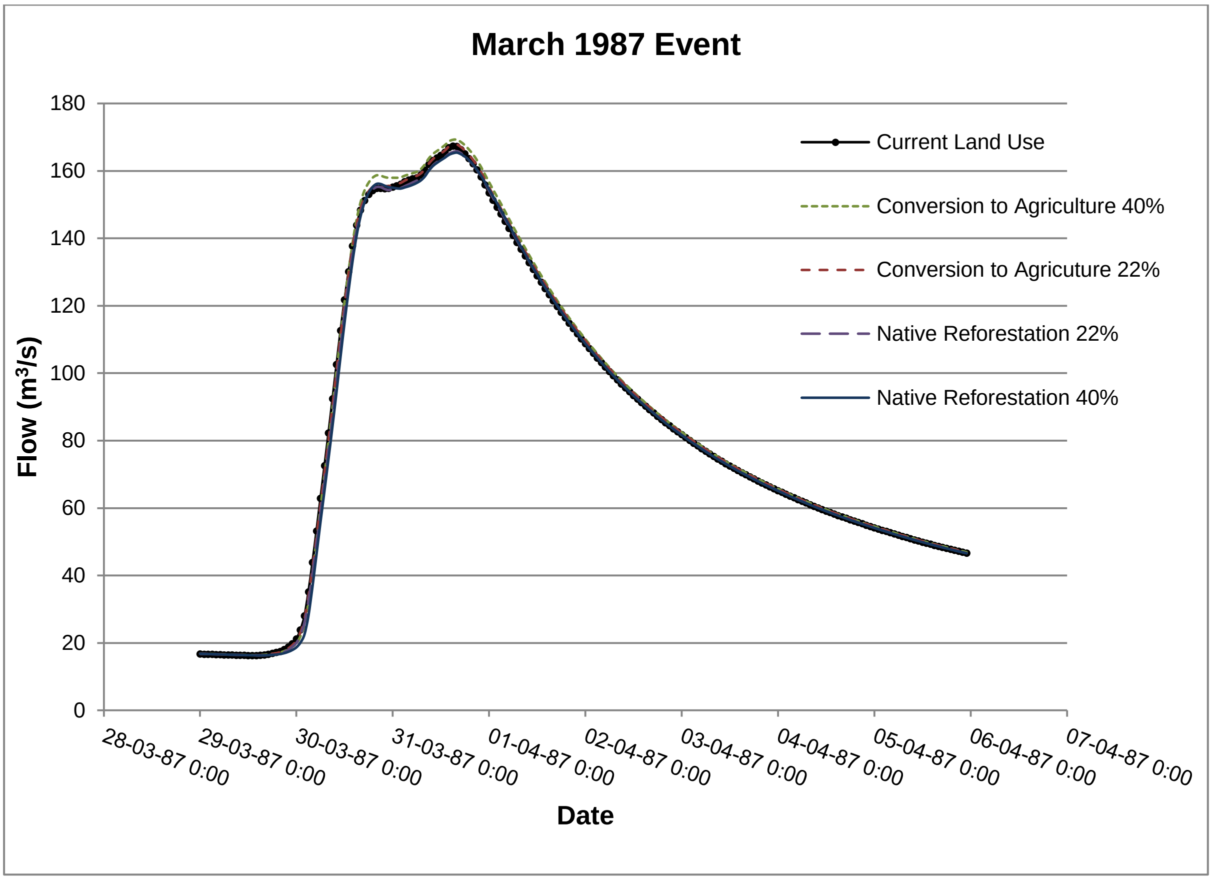
Flood Event	9 Jan 1994	21 Dec 1984	3 Dec 1979	13 Dec 1995	14 Oct 1978	16 Nov 1999	19 Sep 2002	28 Dec 2000	30 Mar 1987
Scenario	Current land use in Ahuriri River catchment								
Peak Flow (m^3/s)	579.4	520.5	268.0	667.2	271.6	359.7	205.6	96.2	167.3
Scenario	Conversion to pasture over 22% of Ahuriri River catchment								
Peak Flow (m^3/s)	586.6	524.0	269.7	671.1	272.1	365.3	206.7	69.8	167.8
Difference in peak flow (m^3/s)	7.2	3.5	1.7	3.9	0.5	5.5	1.1	0.7	0.5
Difference as % of original peak flow	1.2%	0.7%	0.6%	0.6%	0.2%	1.5%	0.5%	0.7%	0.3%
Difference in Time to Peak	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	1 hrs
Scenario	Conversion to pasture over 40% of Ahuriri River catchment								
Peak Flow (m^3/s)	598.0	530.0	278.4	680.8	276.2	369.9	209.7	100.6	169.2
Difference in peak flow (m^3/s)	18.5	9.5	10.5	13.6	4.6	10.2	4.1	4.4	1.9
Difference as % of original peak flow	3.2%	1.8%	3.9%	2.0%	1.7%	2.8%	2.0%	4.6%	1.2%
Difference in Time to Peak	0 hrs	1 hrs	0 hrs	0 hrs	0 hrs	0 hrs	−1 hrs	0 hrs	1 hrs
Scenario	Native reforestation over 22% of Ahuriri River catchment								
Peak Flow (m^3/s)	574.3	514.9	266.5	658.4	268.2	354.7	204.3	96.2	165.8
Difference in peak flow (m^3/s)	-5.2	-5.6	−1.5	−8.8	-3.4	-5.0	−1.3	0.0	−1.5
Difference as % of original peak flow	−0.9%	−1.1%	−0.6%	−1.3%	−1.3%	−1.4%	−0.6%	0.0%	−0.9%
Difference in Time to Peak	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	−1 hrs	0 hrs	1 hrs
Scenario	Native reforestation over 40% of Ahuriri River catchment								
Peak Flow (m^3/s)	570.5	513.6	259.8	657.8	263.9	353.6	202.8	94.6	165.4
Difference in peak flow (m^3/s)	−8.9	−7.0	−8.2	−9.4	−7.7	−6.2	−2.8	−1.6	−1.9
Difference as % of original peak flow	−1.5%	−1.3%	-3.1%	−1.4%	−2.8%	−1.7%	−1.4%	−1.6%	−1.1%
Difference in Time to Peak	0 hrs	1 hrs	0 hrs	0 hrs	1 hrs	0 hrs	−1 hrs	1 hrs	1 hrs

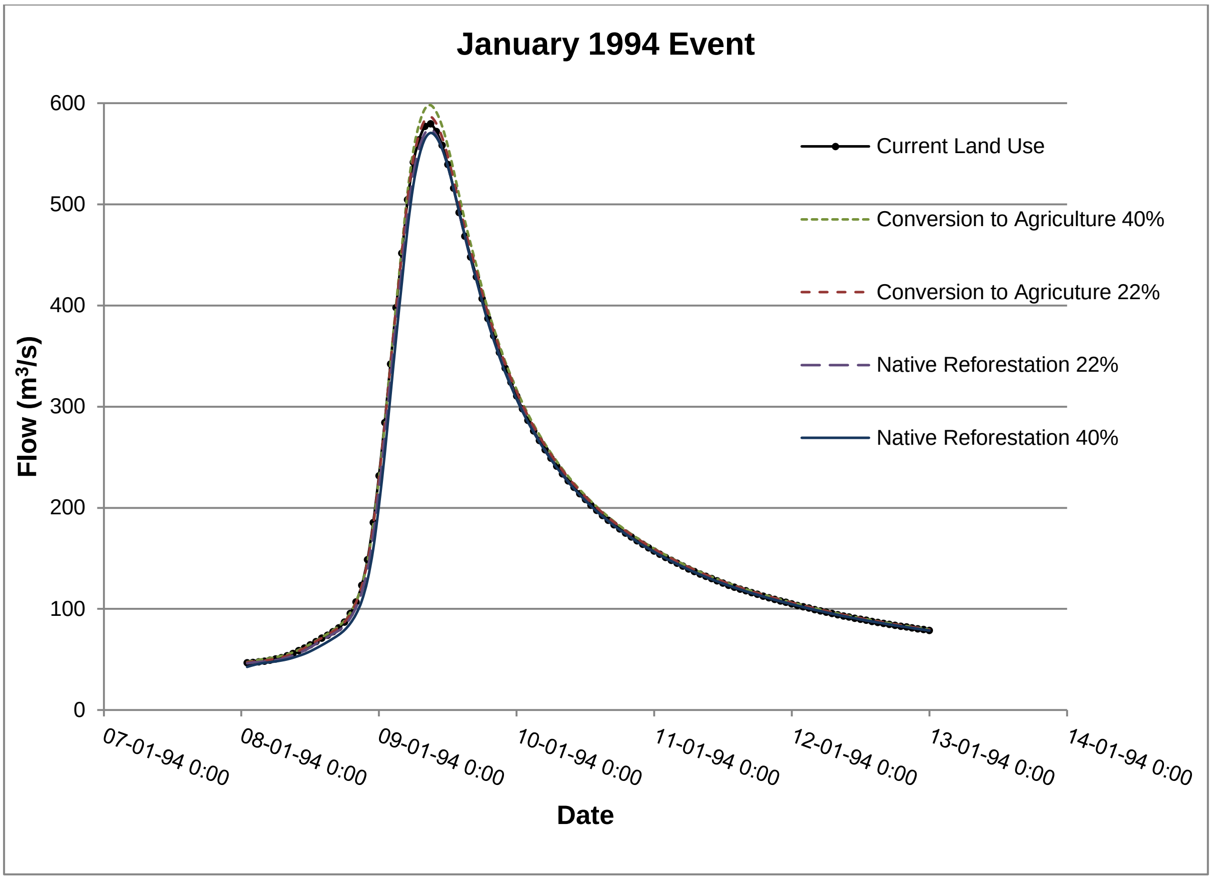
Note: Peak Flow under the current land use scenario is the model prediction and not observed flow.

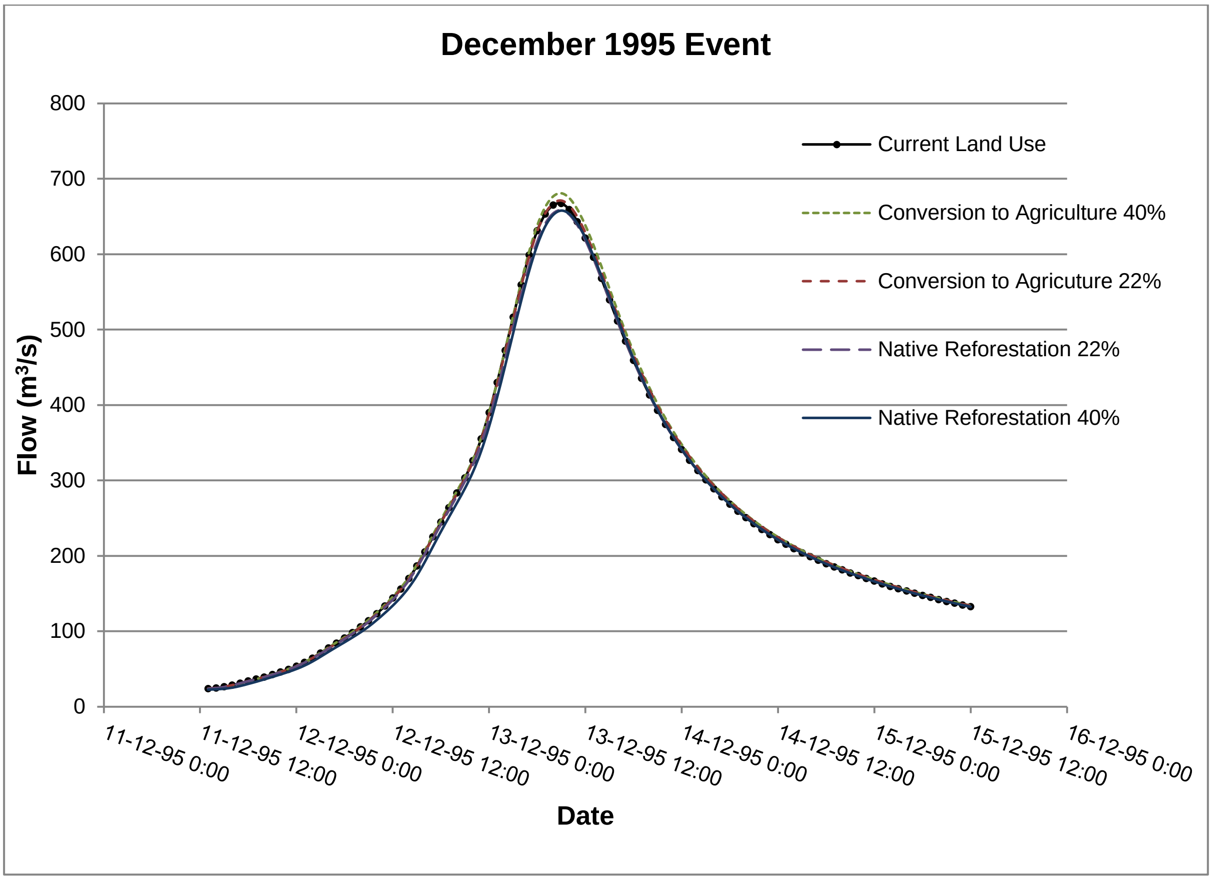

October 1978 Event
Flow (m³/s)
300
250
200
150
100
50
0
12-10-78 12:00
13-10-78 0:00
13-10-78 12:00
14-10-78 0:00
14-10-78 12:00
15-10-78 0:00
15-10-78 12:00
16-10-78 0:00
16-10-78 12:00
17-10-78 0:00
17-10-78 12:00
Date
Current Land Use
Conversion to Agriculture 40%
Conversion to Agriculture 22%
Native Reforestation 22%
Native Reforestation 40%

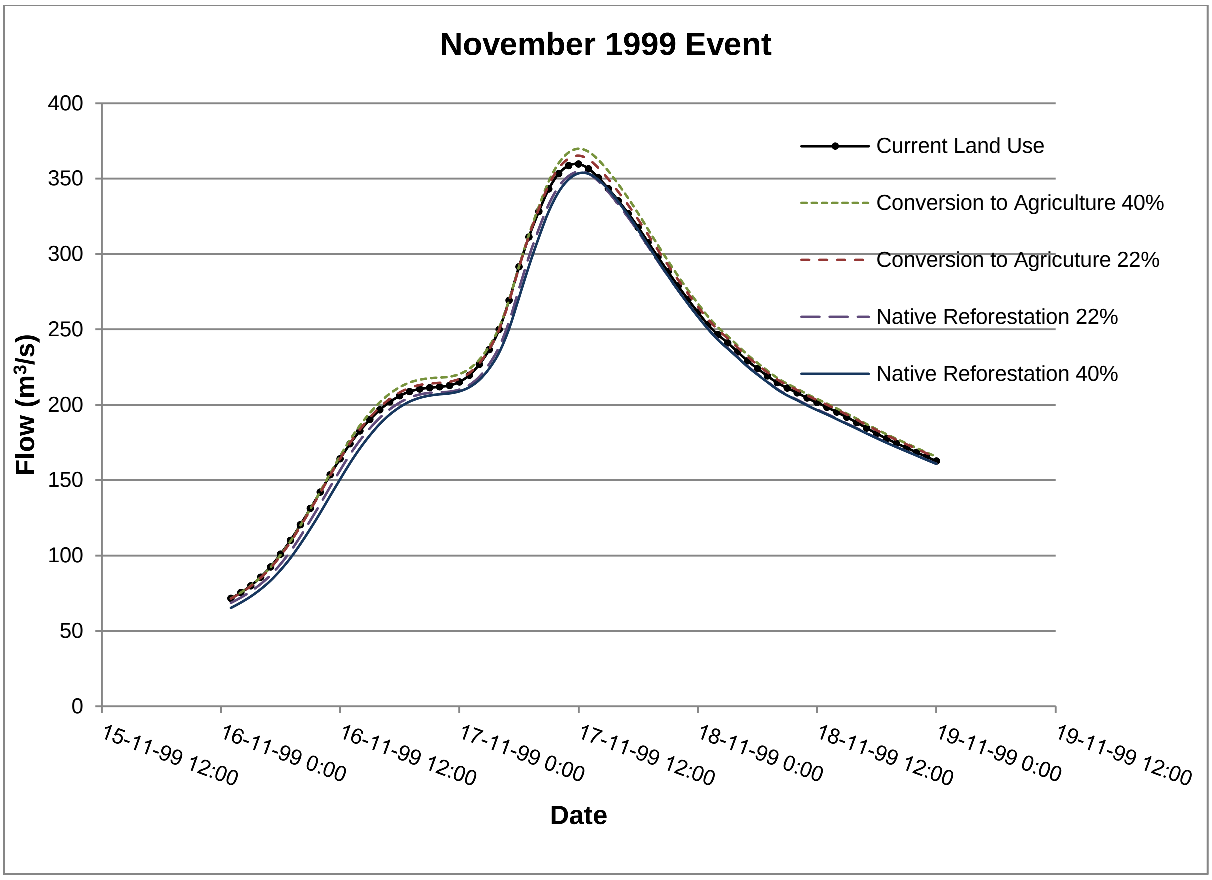

December 1979 Event
Flow (m³/s)
300
250
200
150
100
50
0
01-12-79 0:00
01-12-79 12:00
02-12-79 0:00
02-12-79 12:00
03-12-79 0:00
03-12-79 12:00
04-12-79 0:00
04-12-79 12:00
05-12-79 0:00
05-12-79 12:00
06-12-79 0:00
Date
Current Land Use
Conversion to Agriculture 40%
Conversion to Agriculture 22%
Native Reforestation 22%
Native Reforestation 40%


December 1984 Event
Flow (m³/s)
600
500
400
300
200
100
0
Current Land Use
Conversion to Agriculture 40%
Conversion to Agricuture 22%
Native Reforestation 22%
Native Reforestation 40%
19-12-84 0:00
19-12-84 12:00
20-12-84 0:00
20-12-84 12:00
21-12-84 0:00
21-12-84 12:00
22-12-84 0:00
22-12-84 12:00
23-12-84 0:00
23-12-84 12:00
24-12-84 0:00
Date

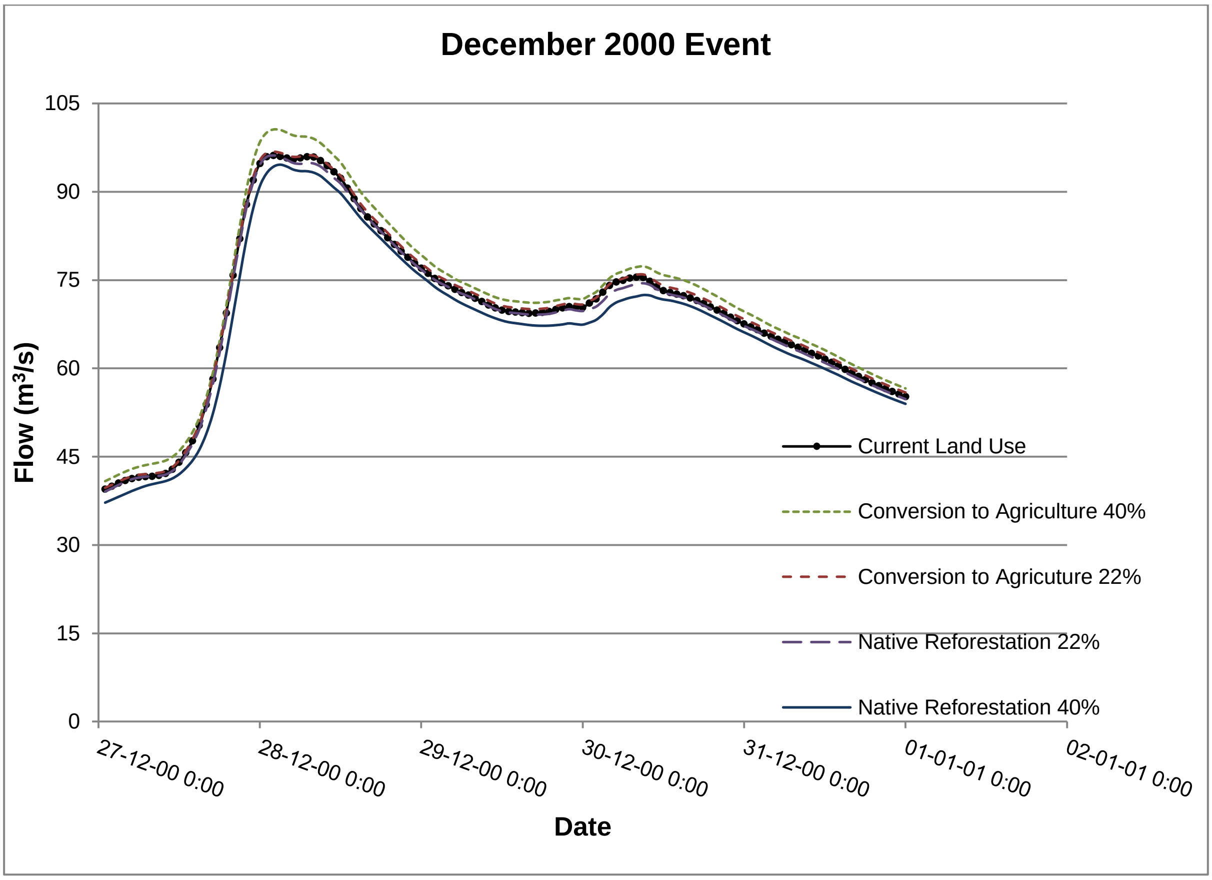

March 1987 Event
Flow (m³/s)
180
160
140
120
100
80
60
40
20
0
Current Land Use
Conversion to Agriculture 40%
Conversion to Agricuture 22%
Native Reforestation 22%
Native Reforestation 40%
28-03-87 0:00
29-03-87 0:00
30-03-87 0:00
31-03-87 0:00
01-04-87 0:00
02-04-87 0:00
03-04-87 0:00
04-04-87 0:00
05-04-87 0:00
06-04-87 0:00
07-04-87 0:00
Date


January 1994 Event
Flow (m³/s)
600
500
400
300
200
100
0
07-01-94 0:00
08-01-94 0:00
09-01-94 0:00
10-01-94 0:00
11-01-94 0:00
12-01-94 0:00
13-01-94 0:00
14-01-94 0:00
Date
Current Land Use
Conversion to Agriculture 40%
Conversion to Agricuture 22%
Native Reforestation 22%
Native Reforestation 40%

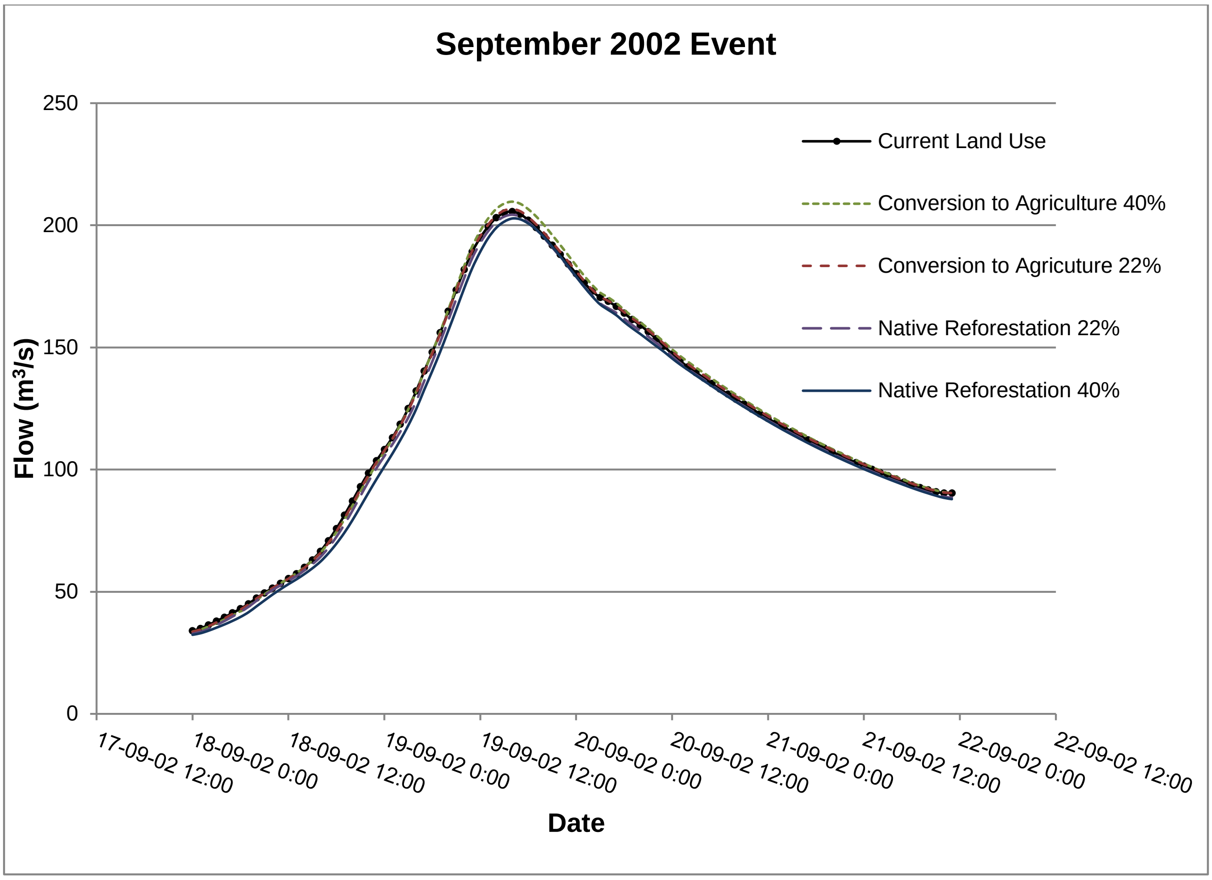

December 1995 Event
Flow (m³/s)
800
700
600
500
400
300
200
100
0
11-12-95 0:00
11-12-95 12:00
12-12-95 0:00
12-12-95 12:00
13-12-95 0:00
13-12-95 12:00
14-12-95 0:00
14-12-95 12:00
15-12-95 0:00
15-12-95 12:00
16-12-95 0:00
Date
Current Land Use
Conversion to Agriculture 40%
Conversion to Agriculture 22%
Native Reforestation 22%
Native Reforestation 40%



November 1999 Event
Flow (m³/s)
400
350
300
250
200
150
100
50
0
15-11-99 12:00
16-11-99 0:00
16-11-99 12:00
17-11-99 0:00
17-11-99 12:00
18-11-99 0:00
18-11-99 12:00
19-11-99 0:00
19-11-99 12:00
Date
Current Land Use
Conversion to Agriculture 40%
Conversion to Agricuture 22%
Native Reforestation 22%
Native Reforestation 40%



December 2000 Event
Flow (m³/s)
105
90
75
60
45
30
15
0
27-12-00 0:00
28-12-00 0:00
29-12-00 0:00
30-12-00 0:00
31-12-00 0:00
01-01-01 0:00
02-01-01 0:00
Date
Current Land Use
Conversion to Agriculture 40%
Conversion to Agricuture 22%
Native Reforestation 22%
Native Reforestation 40%

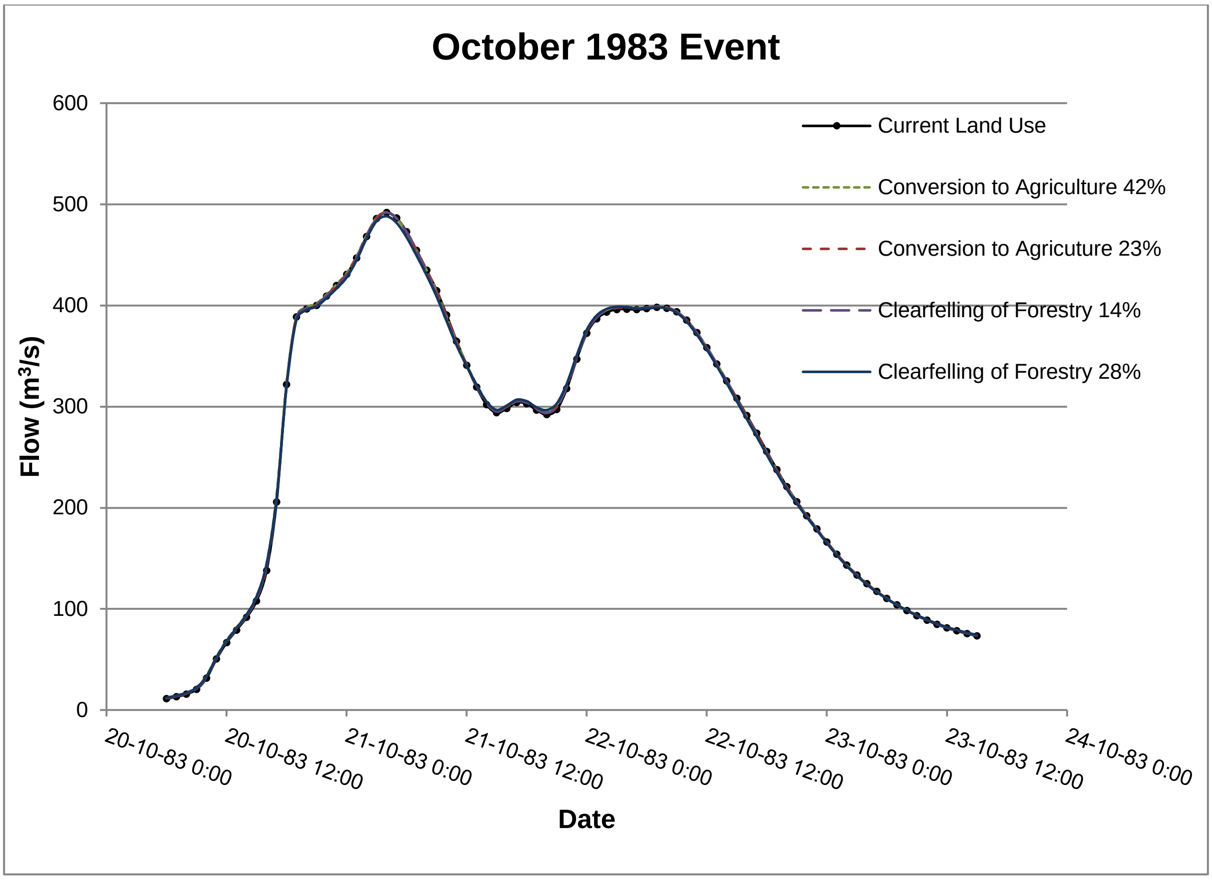

September 2002 Event
Flow (m³/s)
250
200
150
100
50
0
Current Land Use
Conversion to Agriculture 40%
Conversion to Agricuture 22%
Native Reforestation 22%
Native Reforestation 40%
17-09-02 12:00
18-09-02 0:00
18-09-02 12:00
19-09-02 0:00
19-09-02 12:00
20-09-02 0:00
20-09-02 12:00
21-09-02 0:00
21-09-02 12:00
22-09-02 0:00
22-09-02 12:00
Date

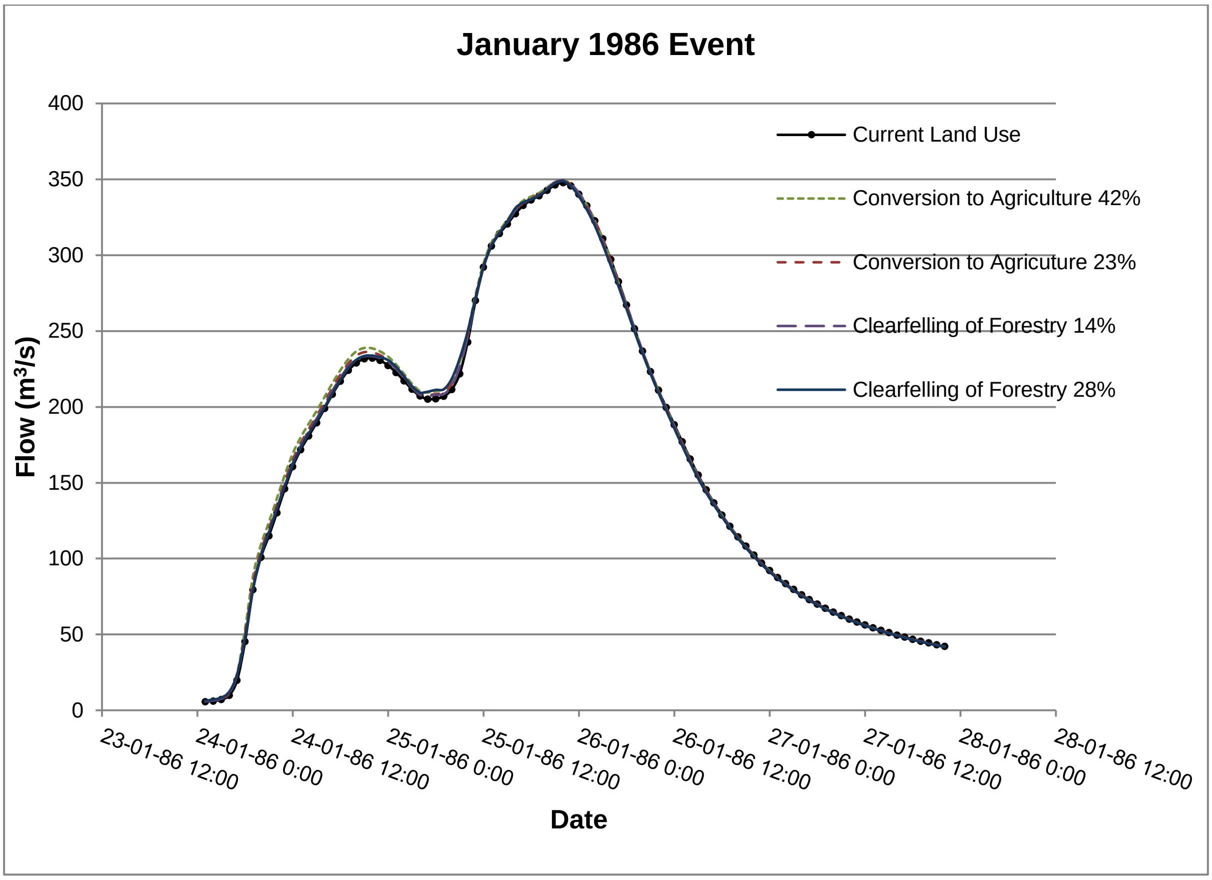
Pelorus River Catchment

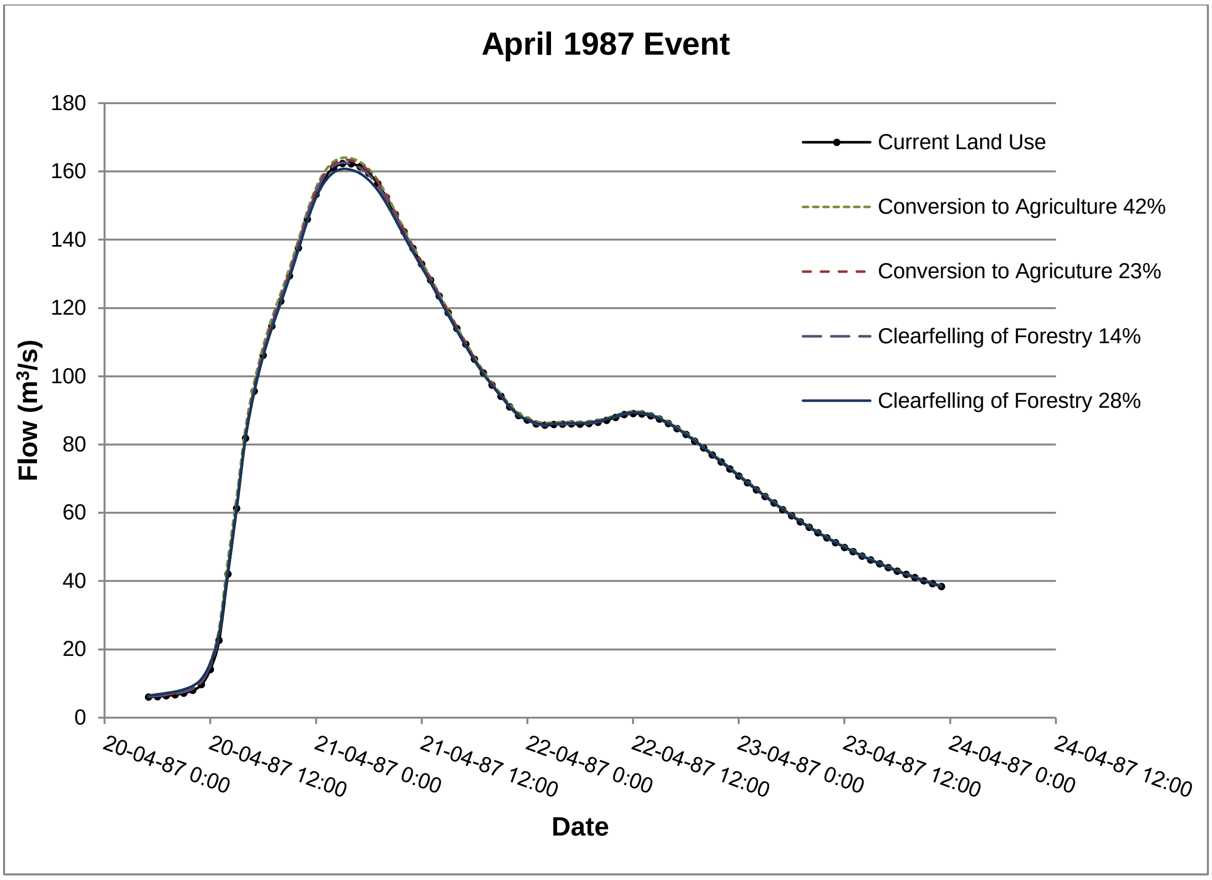
Results of modelling land use change scenarios, Pelorus River catchment

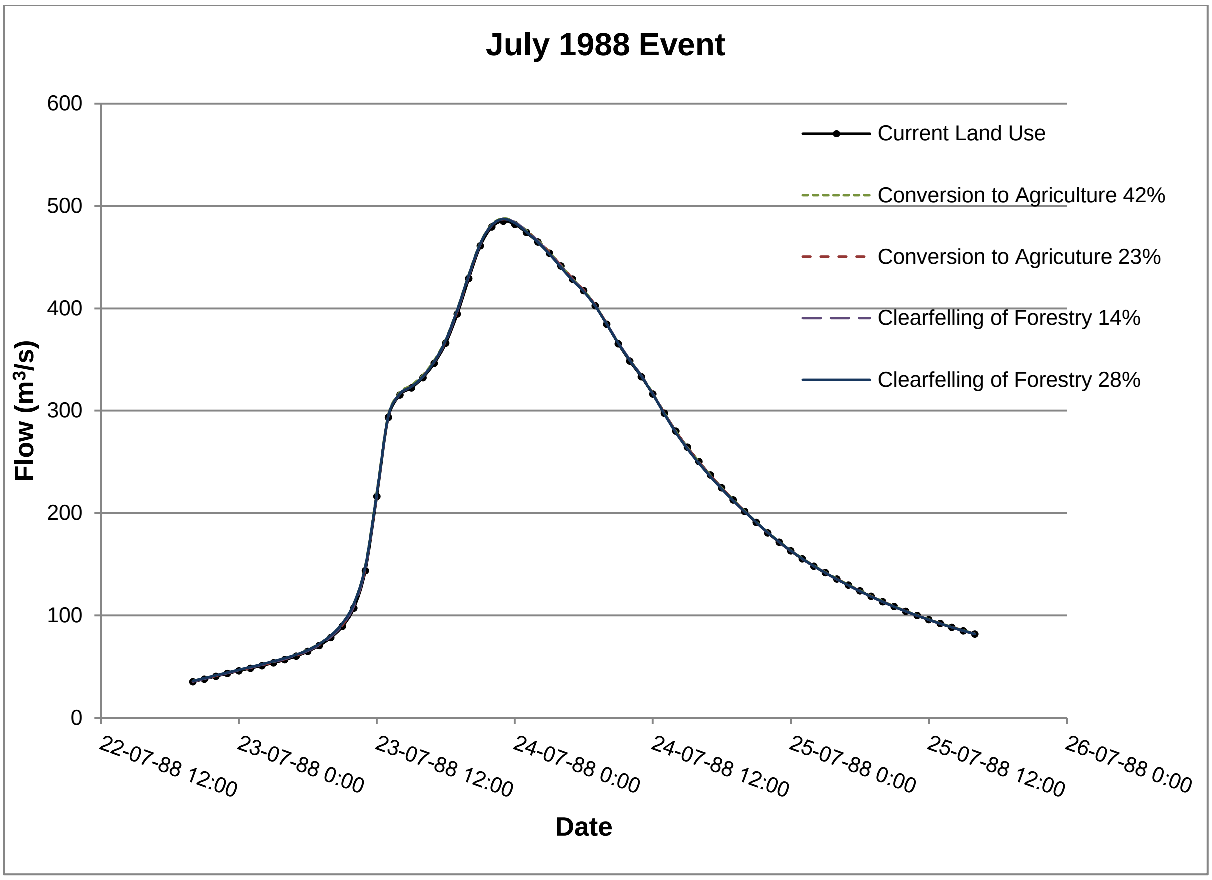
Flood Event	21 Oct 1983	1 July 1998	23 Feb 1995	30 Jan 2000	23 July 1988	25 Jan 1986	13 June 1993	24 Jan 1991	21 Apr 1987
Scenario	Current land use in Pelorus River catchment								
Peak Flow (m^3/s)	491.9	1012.9	295.4	352.2	485.2	347.7	407.8	259.5	162.3
Scenario	Conversion to pasture over 23% of Pelorus River catchment								
Peak Flow (m^3/s)	491.9	1015.5	295.5	357.3	487.1	348.9	409.3	261.3	163.3
Difference in peak flow (m^3/s)	0.0	2.6	0.1	5.1	1.9	1.2	1.6	1.8	1.1
Difference as % of original peak flow	0.0%	0.3%	0.0%	1.4%	0.4%	0.3%	0.4%	0.7%	0.7%
Difference in Time to Peak	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs
Scenario	Conversion to pasture over 42% of Pelorus River catchment								
Peak Flow (m^3/s)	492.0	1016.1	295.5	359.7	487.8	349.4	409.6	265.5	164.0
Difference in peak flow (m^3/s)	0.2	3.2	0.0	7.5	2.6	1.7	1.8	6.0	1.7
Difference as % of original peak flow	0.0%	0.3%	0.0%	2.1%	0.5%	0.5%	0.4%	2.3%	1.1%
Difference in Time to Peak	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs
Scenario	Forest harvest and clearfelling over 14% of Pelorus River catchment								
Peak Flow (m^3/s)	491.8	1015.9	295.1	355.0	487.3	349.3	409.1	260.9	162.5
Difference in peak flow (m^3/s)	−0.2	3.0	−0.4	2.8	2.1	1.6	1.3	1.3	0.3
Difference as % of original peak flow	−0.0%	0.3%	−0.1%	0.8%	0.4%	0.5%	0.3%	0.5%	0.2%
Difference in Time to Peak	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs
Scenario	Forest harvest and clearfelling over 28% of Pelorus River catchment								
Peak Flow (m^3/s)	488.1	1016.6	291.3	354.2	487.2	348.7	407.9	261.5	161.0
Difference in peak flow (m^3/s)	-3.8	3.7	−4.2	2.0	2.0	1.0	0.2	1.9	−1.6
Difference as % of original peak flow	−0.8%	0.4%	−1.4%	0.6%	0.4%	0.3%	0.0%	0.7%	−1.0%
Difference in Time to Peak	0 hrs	0 hrs	−1 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs	0 hrs

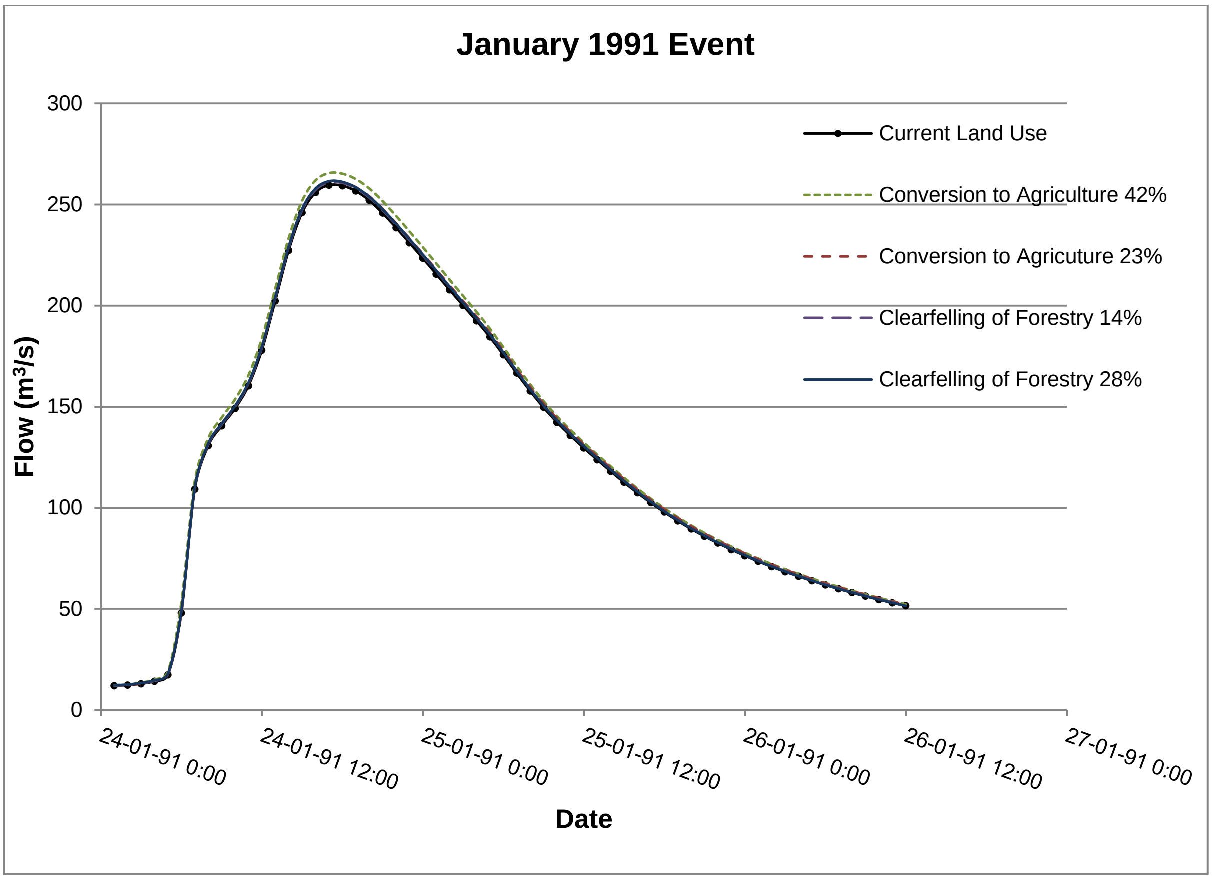
Note: Peak Flow under the current land use scenario is the model prediction and not observed flow.

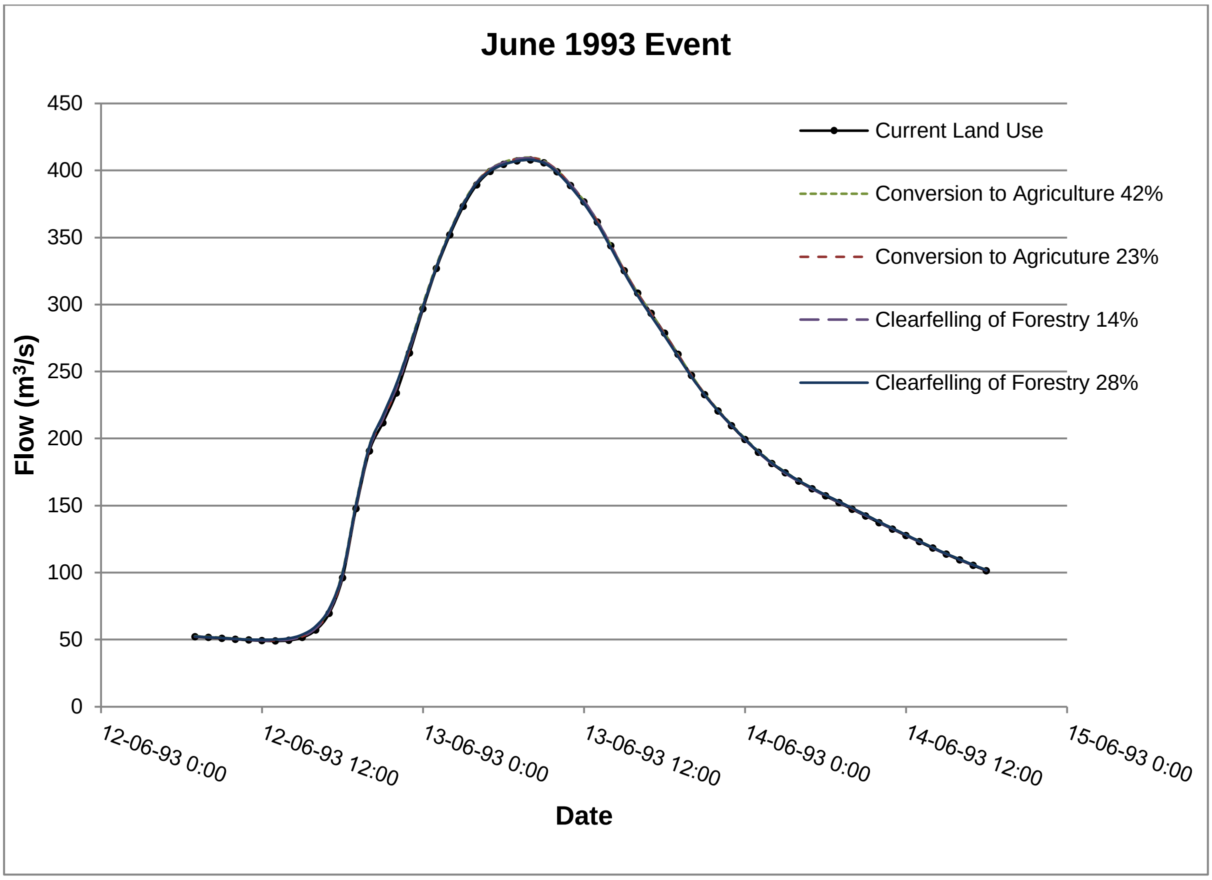

October 1983 Event
Flow (m³/s)
600
500
400
300
200
100
0
Current Land Use
Conversion to Agriculture 42%
Conversion to Agriculture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
20-10-83 0:00
20-10-83 12:00
21-10-83 0:00
21-10-83 12:00
22-10-83 0:00
22-10-83 12:00
23-10-83 0:00
23-10-83 12:00
24-10-83 0:00
Date

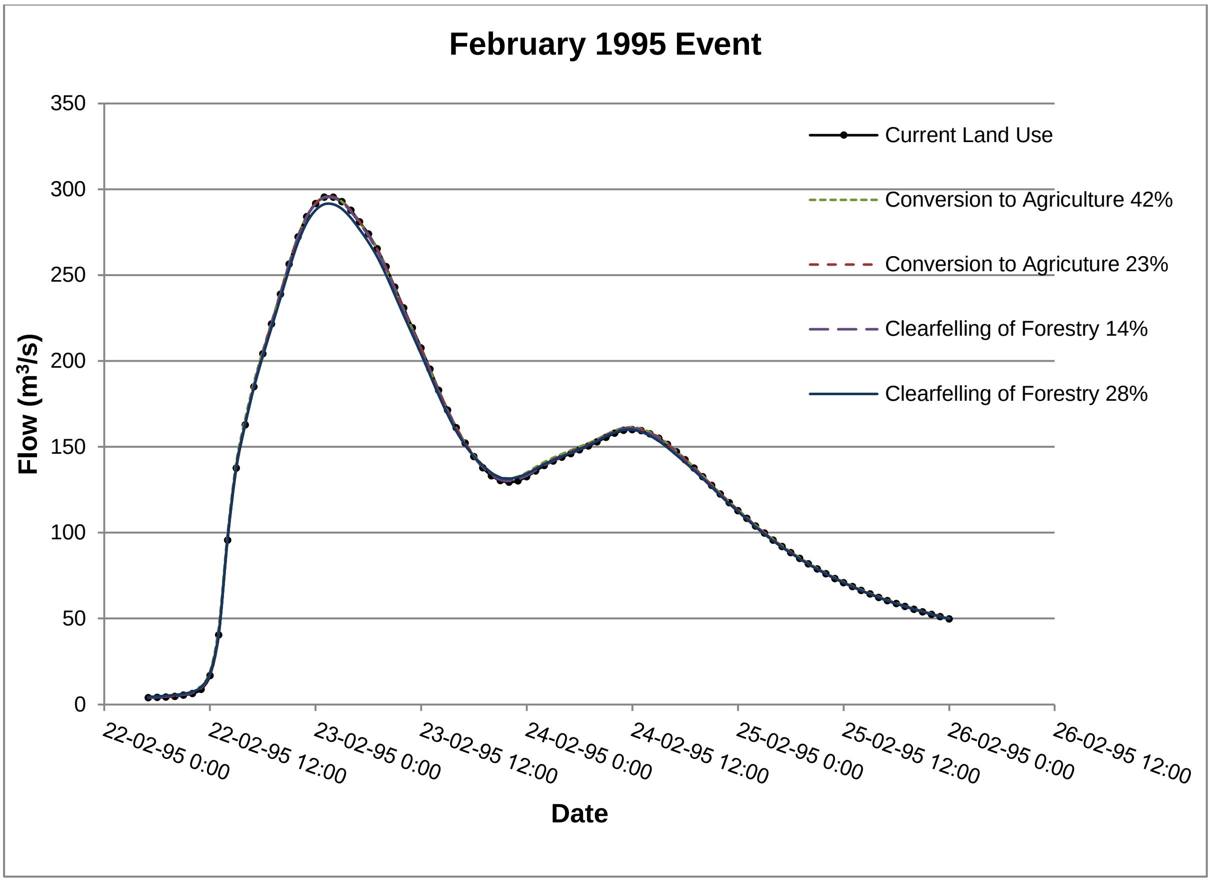

January 1986 Event
Flow (m³/s)
400
350
300
250
200
150
100
50
0
Current Land Use
Conversion to Agriculture 42%
Conversion to Agriculture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
23-01-86 12:00
24-01-86 0:00
24-01-86 12:00
25-01-86 0:00
25-01-86 12:00
26-01-86 0:00
26-01-86 12:00
27-01-86 0:00
27-01-86 12:00
28-01-86 0:00
28-01-86 12:00
Date

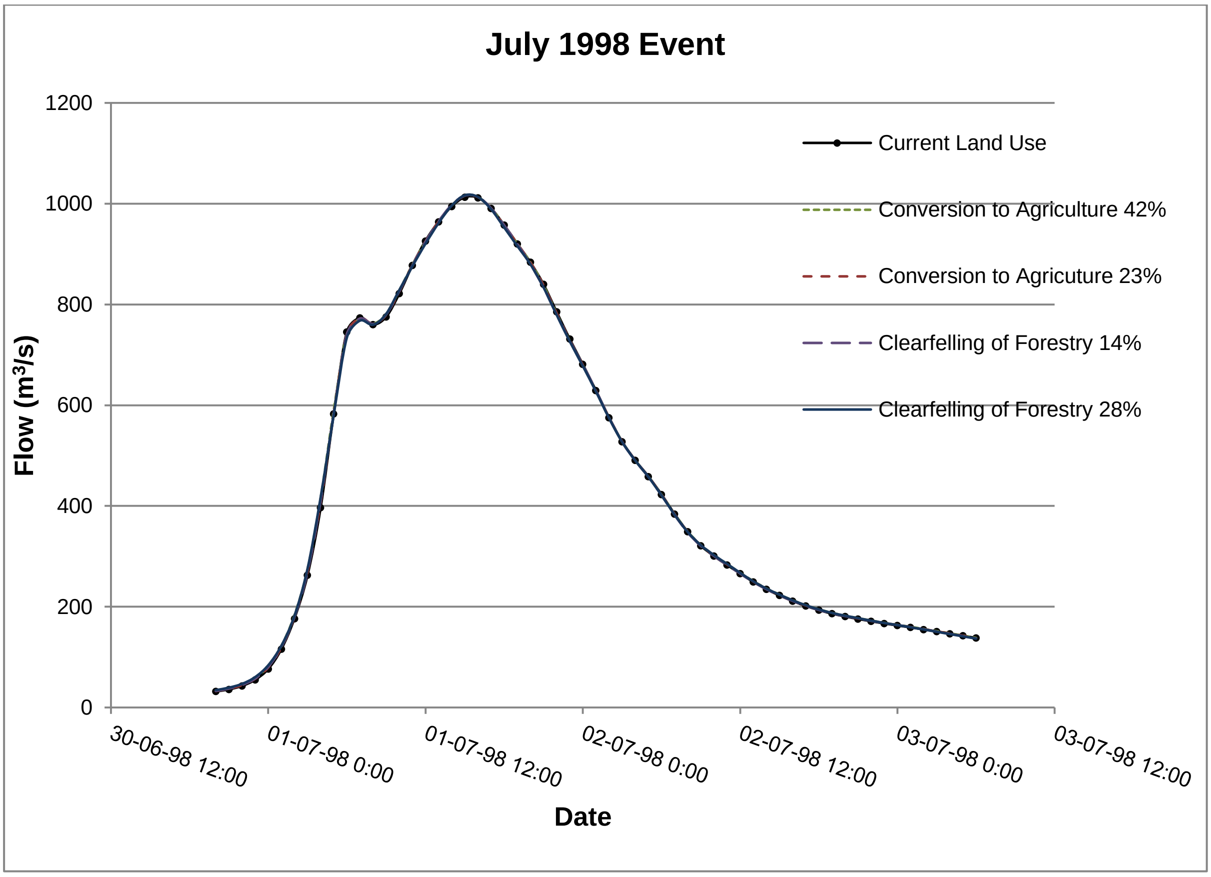

April 1987 Event
Flow (m³/s)
Date
Current Land Use
Conversion to Agriculture 42%
Conversion to Agriculture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
0
20
40
60
80
100
120
140
160
180
20-04-87 0:00
20-04-87 12:00
21-04-87 0:00
21-04-87 12:00
22-04-87 0:00
22-04-87 12:00
23-04-87 0:00
23-04-87 12:00
24-04-87 0:00
24-04-87 12:00

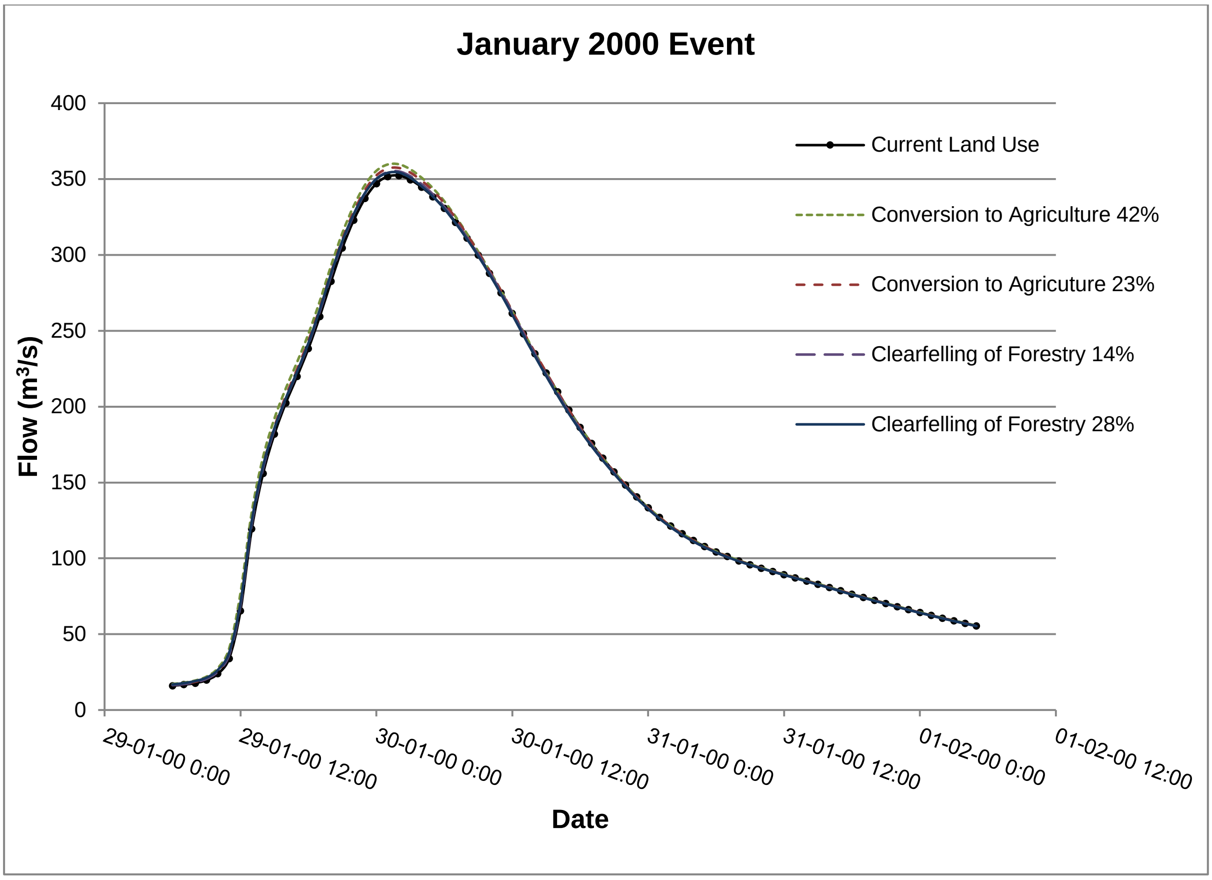

July 1988 Event
Flow (m³/s)
Date
Current Land Use
Conversion to Agriculture 42%
Conversion to Agriculture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
0
100
200
300
400
500
600
22-07-88 12:00
23-07-88 0:00
23-07-88 12:00
24-07-88 0:00
24-07-88 12:00
25-07-88 0:00
25-07-88 12:00
26-07-88 0:00


January 1991 Event
Flow (m³/s)
300
250
200
150
100
50
0
Current Land Use
Conversion to Agriculture 42%
Conversion to Agricuture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
24-01-91 0:00
24-01-91 12:00
25-01-91 0:00
25-01-91 12:00
26-01-91 0:00
26-01-91 12:00
27-01-91 0:00
Date


June 1993 Event
Flow (m³/s)
450
400
350
300
250
200
150
100
50
0
Current Land Use
Conversion to Agriculture 42%
Conversion to Agricuture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
12-06-93 0:00
12-06-93 12:00
13-06-93 0:00
13-06-93 12:00
14-06-93 0:00
14-06-93 12:00
15-06-93 0:00
Date


February 1995 Event
Flow (m³/s)
Date
Current Land Use
Conversion to Agriculture 42%
Conversion to Agricuture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
350
300
250
200
150
100
50
0
22-02-95 0:00
22-02-95 12:00
23-02-95 0:00
23-02-95 12:00
24-02-95 0:00
24-02-95 12:00
25-02-95 0:00
25-02-95 12:00
26-02-95 0:00
26-02-95 12:00


July 1998 Event
Flow (m³/s)
Date
Current Land Use
Conversion to Agriculture 42%
Conversion to Agriculture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%
1200
1000
800
600
400
200
0
30-06-98 12:00
01-07-98 0:00
01-07-98 12:00
02-07-98 0:00
02-07-98 12:00
03-07-98 0:00
03-07-98 12:00



January 2000 Event
Flow (m3/s)
400
350
300
250
200
150
100
50
0
29-01-00 0:00
29-01-00 12:00
30-01-00 0:00
30-01-00 12:00
31-01-00 0:00
31-01-00 12:00
01-02-00 0:00
01-02-00 12:00
Date
Current Land Use
Conversion to Agriculture 42%
Conversion to Agricuture 23%
Clearfelling of Forestry 14%
Clearfelling of Forestry 28%